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The Geology, Geochemistry, and Sulfur Isotopes

of the Anyox Massive Sulfide Deposits

by

©  Robert J. Sharp

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

GEOLOGY

DEPARTMENT ....GEOLOGY....................

EDMONTON, ALBERTA

(SPRING), (1980)

DEDICATION

This is dedicated to Aritha, who really helped.

ABSTRACT

Tholeiitic metabasaltic pillow lavas either host or underlie a number of cupriferous massive sulfide deposits near Anyox, British Columbia. The Hidden Creek, Double Ed, and Bonanza copper deposits are three volcanogenic massive pyrite-pyrrhotite-chalcopyrite orebodies which have attracted mining and exploration investment at Anyox since the early 1900s. The Hidden Creek deposit is characterized by tabular, cupriferous iron sulfide bodies which lie conformably along a major volcanic-sedimentary contact. A large unit of altered metabasalt stratigraphically underlies the stratiform sulfide interbeds. Epigenetic, sulfide-bearing quartz stockworks crosscut an alteration zone and extend to the base of the overlying stratiform deposits. The Double Ed and Bonanza deposits are hosted by pillowed metabasaltic lava and occur 150 m stratigraphically below the main volcanic-sedimentary contact at Anyox. These two deposits are narrow, pipe-like orebodies which are conformable with their metavolcanic host rocks. Small alteration zones are associated with each deposit. Analyses for major elements show the original basaltic magma to have been tholeiitic. Comparison of analyses between the altered and unaltered metabasalts defines chemical trends of rock alteration by hydrothermal fluids. Altered basalts have gained iron, sulfur, and magnesium, but have lost calcium, silica and sodium. Analyses reveal weak to strong copper enrichments in the altered rocks. Yttrium, niobium, chromium, and zirconium

abundances in the unaltered metabasalt suggest that the ore deposits formed in an ocean basin. Trace element contents of the metamorphosed chert layer (along the volcanic-sedimentary contact) at the Hidden Creek mine indicate that there was little exhalative dispersion of metals away from the orebodies.

Sulfur isotopes in the three deposits fall in the +1.5 to +6.7 $\delta^{34}S$ (‰) range. The Double Ed and Bonanza deposits show little time and space variations in sulfur isotopes. The Hidden Creek deposit shows a trend of decreasing $\delta^{34}S$ values in time and space, similar to that observed for the type Kuroko deposits of Japan. Pyrite-chalcopyrite pairs revealed sulfur isotope temperatures equivalent to greenschist grade metamorphism (+450°C); other sulfur isotope temperatures ranged from +676°C to +1227°C and are believed to be related to post-mineralization dikes. The main source of sulfur was apparently Upper Triassic seawater.

The environment of ore deposition in all three deposits was probably similar to that of the present day Red Sea metalliferous muds. It is postulated that seawater was cycled into a geothermal system within the volcanic pile. The brine was heated and underwent reduction and chemical exchange with the basaltic rocks. The resultant ore solutions then percolated out onto the sea floor and accumulated in depressions near the hot springs. Capping by lava flows or sediments subsequently preserved the deposits form erosion. Similar cupriferous massive sulfide deposits are found at Løkken, Norway; Besshi, Japan; Cyprus; the Whalesback mine, Newfoundland; and at the Goldstream locality in British Columbia.

## ACKNOWLEDGMENTS

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# CHAPTER I

# INTRODUCTION

The Anyox district was one of the most important copper mining camps in British Columbia during the first half of the twentieth century. A copper smelter operated at the Anyox townsite from 1914 until 1935. The main copper producer during this period was the Hidden Creek mine, located several kilometers north of the smelter complex. Although production has been nil from 1935 to the present, a major mining company (Cominco Limited) holds mineral title to most of the important copper deposits in the area.

## LOCATION AND ACCESS

The Anyox townsite is located on tidewater at 55°25' north latitude and 129°50' west longitude, approximately 130 km northeast of Prince Rupert, British Columbia. Access into the area is available using either float-equipped aircraft or boat from Prince Rupert. Figure 1 shows the location of Anyox.

## TOPOGRAPHY AND VEGETATION

The terrain at Anyox ranges from low, rolling hills near the ocean to rugged mountains inland; elevations vary from sea level to 1525 m. Forest cover is sparse to dense. In the vicinity of the smelter and Anyox townsite, vegetation consists only of small shrubs and bushes because the soil was damaged by smelter fumes. Numerous

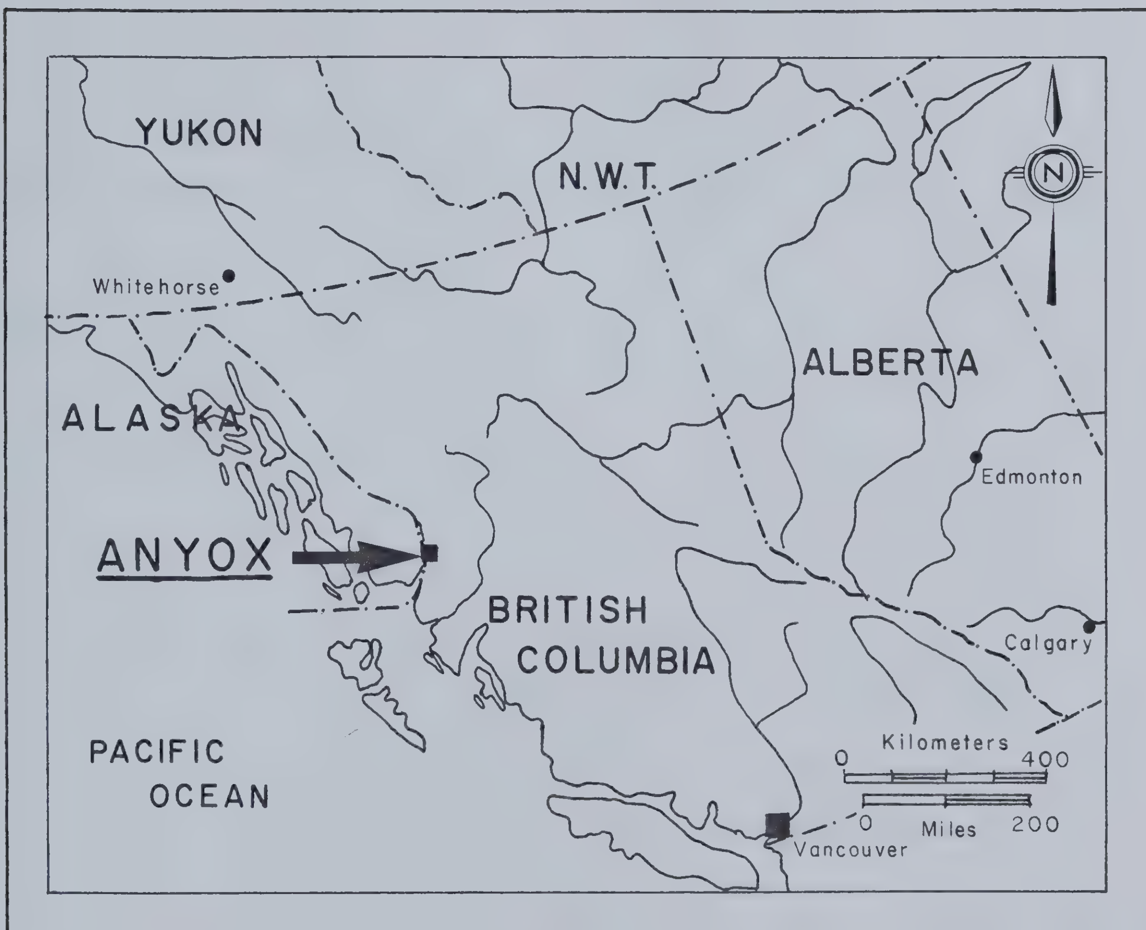



Figure 1. Location of the Anyox area, British Columbia.

forest fires have burnt over much of the area, but elsewhere, dense coastal rainforests cover the mountainsides.

## HISTORY

### Mining

The Hidden Creek deposit was staked by prospectors in 1901 and in the same year sold to the Hidden Creek Copper Company, directed by M. K. Rodgers. Further exploration proved successful and the property was sold to the Granby Consolidated Mining, Smelting and Power Company Limited in 1911. Major development work commenced on the Hidden Creek orebody and a smelter was constructed at the Anyox townsite. The smelter was "blown in" in 1914 and full scale production started at that time. The Hidden Creek mine produced 3000 tons of ore per day at a grade of about 2% copper. Ore was directly smelted in blast furnaces until 1924, when a concentrator was built. After 1928, additional ore came from the Bonanza mine via a tramline between mine and smelter. From 1925 to 1935 the mill feed ranged between 1.16 and 1.54% copper, with concentrates averaging 16.5% copper. The matte from the blast furnaces was blown to blister copper in converters and then shipped to the Nichols Chemical Company in New York for refining. In 1935, depressed world copper prices, low ore grade, and higher mining costs resulted in closure of the mine and the smelting complex. The Consolidated Mining and Smelting Company of Canada Limited (now Cominco Limited) purchased the entire mining, smelting, and townsite complex in late 1935. All usable equipment from the mine and smelter was salvaged by Cominco, and transported to Trail, British Columbia.

### Mineral Exploration

Cominco Limited carried out local exploration around the Hidden Creek mine as well as work on a regional scale in the Anyox pendant from 1937 to 1976. The Double Ed and Eden properties (see figure 2) were located in 1952 by Cominco prospectors. Exploration on the Double Ed property was conducted from 1952 until 1960 and consisted of diamond drilling as well as construction of an adit 820 m long for underground exploration and drilling.

## PREVIOUS GEOLOGICAL INVESTIGATIONS

The Annual Report issued by the British Columbia Ministry of Energy, Mines and Petroleum Resources, from 1910 to the present, contains brief geological notes on the properties in the Anyox area, along with production data from the mines. The geology of the area was described by McConnell (1912), Dolmage (1922), Hanson (1935), and Nelson (1935). A regional geological compilation map was published by Grove and Carter in 1972.

## WRITER'S RESEARCH

The writer spent two and one half months in the Anyox area during the summer of 1976, while employed by Cominco Limited. The company program consisted of regional and detailed geological mapping, rock sampling, and re-examination of old diamond drill core. Underground mapping and sampling were conducted on the Double Ed deposit. Geological data and rock samples were gathered for thesis research at that time.

The copper mineralization at Anyox has always been considered to be epigenetic, formed when hydrothermal solutions replaced the host

# LEGEND

## TERTIARY

| | | |
|---|---|---|
| 6 | COAST PLUTONIC COMPLEX: | Quartz diorite, granodiorite, quartz monzonite |
| 5 | ALICE ARM INTRUSIONS: | Porphyritic quartz monzonite |

## MIDDLE TO UPPER JURASSIC

| | | |
|---|---|---|
| 4 | BOWSER LAKE GROUP: | Siltstone, sandstone, greywacke, shale, conglomerate and coal |

## LOWER TO MIDDLE JURASSIC

| | | |
|---|---|---|
| 3 | HAZELTON GROUP: | Varicolored basaltic to rhyolitic volcanic rocks and sediments |

## TRIASSIC TO LOWER JURASSIC

| | | |
|---|---|---|
| 2 | Metasedimentary Rocks. | Argillite: impure quartzite, shale. Calcareous siltstone, sandstone. |
| 1 | Metabasalt. | Pillowed lava flows, basaltic dikes and sills. Minor tuffs and intercalated metasedimentary rocks. |

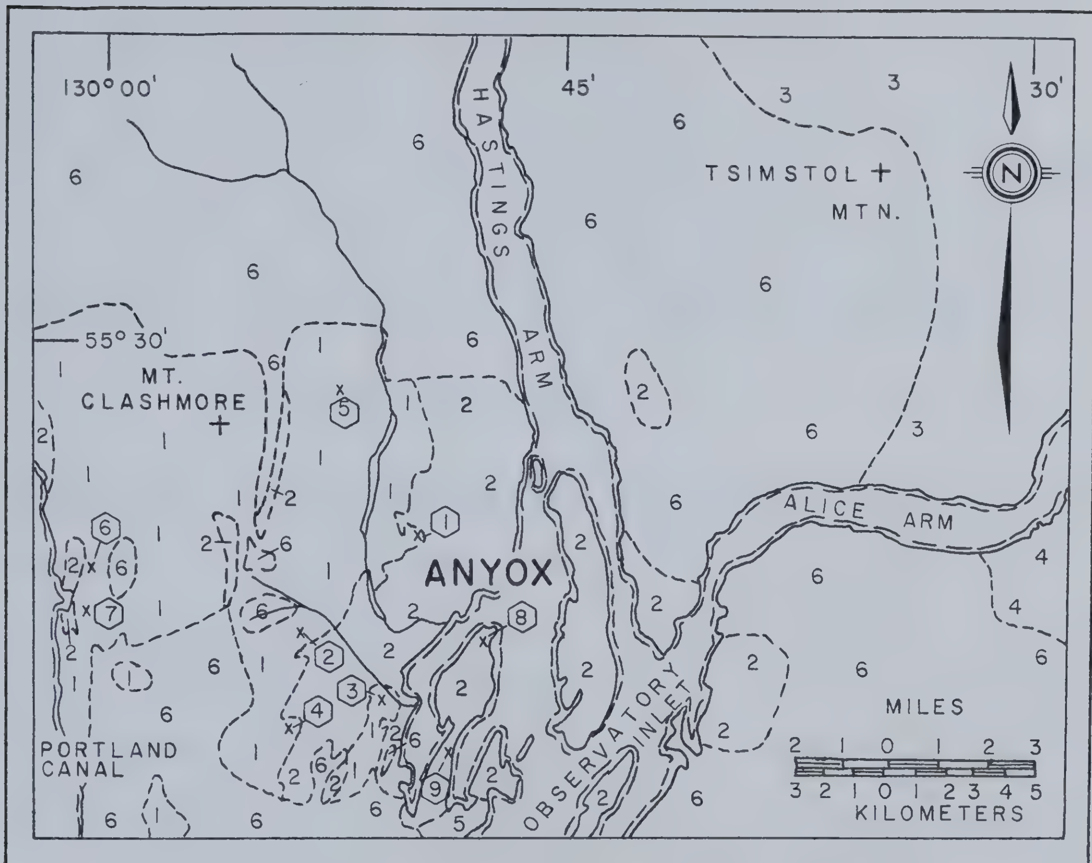



Figure 2. Geology of the Anyox Area, British Columbia (modified after Carter and Grove, 1972).

SYMBOLS

| | |
|---|---|
| Geological Contact | ---------- |
| Coastline | |
| Mineral Deposit | ⬡ |

MINERAL DEPOSITS

| | | | | | |
|---|---|---|---|---|---|
| 1 | Hidden Creek | Cu, Zn | 6 | Outsider | Cu |
| 2 | Double Ed | Cu, Zn | 7 | Eagle | Cu |
| 3 | Bonanza | Cu, Zn | 8 | Granby Bay | Au |
| 4 | Redwing | Cu, Zn | 9 | Nabob | Au |
| 5 | Eden | Cu, Zn | | | |

rocks with sulfide minerals in shear zones (McConnell, 1912; Dolmage, 1922; Hanson, 1935; Nelson, 1935). Based on extensive research, the writer puts forward the thesis that the Hidden Creek, Double Ed and Bonanza copper deposits were hot spring sinters formed on the sea floor during breaks in volcanism, and are directly related to hydrothermal processes that were active in the newly formed basaltic volcanic pile.

## MASSIVE SULFIDE DEPOSITS

Five significant deposits of cupriferous massive sulfide have been discovered in metabasaltic rocks near Anyox, British Columbia. Two deposits are located near Maple Bay in rocks similar to those hosting the Anyox deposits. Figure 2 and figure 3 (in pocket) show the location of the deposits and Table 1 lists the deposits and their contained metal values. Figure 2 is modified after Carter and Grove (1972), and figure 3 is a compilation based on the writer's mapping plus previous mapping carried out by the Granby Consolidated Mining, Smelting and Power Company Limited, and later by Cominco Limited.

The Hidden Creek, Double Ed and Bonanza deposits were studied in detail by the writer. Emphasis was placed on mapping the massive sulfide deposits and the rocks that enclose them; these data are presented as geological maps shown in figures 4 through 8, inclusive. Figure 4 is a map showing the detailed surface geology of the Hidden Creek mine; figures 4A-A' and 4B-B' are geological cross-sections through the mine area. These are the major figures for the Hidden Creek deposit and are located in the pocket at the back of this thesis. The surface geology of the Double Ed deposit is illustrated in figures 5 and 6;

Table 1. Metal Contents of the Anyox Deposits (Data from Minfile, 1979 and Grove, 1965)

| NO. | DEPOSIT | PAST PRODUCTION | | | | PRESENT RESERVES | | | | TOTAL METAL CONTENT |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Tonnes | Grade (%) Cu | Grade (%) Zn | Metal Content (kg) | Tonnes | Grade (%) Cu | Grade (%) Zn | Metal Content (kg) | |
| 1 | Hidden Creek | 21,725,527 | 1.55 | NA* | 336,745,670 | 18,144,000 | 0.46 | NA | 83,462,400 | 420,208,070 |
| 2 | Bonanza | 656,973 | 2.18 | NA | 14,322,011 | 226,800 | 1.0 | NA | 2,268,000 | 16,590,011 |
| 3a | Double Ed | NIL | - | - | - | 3,628,800 | 1.0 | - | 36,288,000 | 36,288,000 |
| 3b | Double Ed | NIL | - | - | - | 3,628,800 | - | 0.6 | 21,722,800 | 21,722,800 |
| 4 | Redwing | NIL | - | - | - | 181,440 | 2.0 | - | 3,628,800 | 3,628,800 |
| 5 | Eden | NIL | - | - | - | 226,800 | 2.0 | - | 4,536,000 | 4,536,000 |
| 6 | Outsider | 16,000 | 2.9 | - | 464,000** | 181,440 | 1.5 | - | 2,721,600 | 3,185,600 |
| 7 | Eagle | 96,000 | 1.77 | - | 1,699,200*** | | | | | |
| | (a) Indicated | | | | | 473,558 | 1.71 | - | 8,097,842 | |
| | (b) Inferred | | | | | 535,248 | 1.4 | - | 7,493,472 | |
| | Total | | | | | | | | | 17,290,514 |
| | TOTALS | | | | 353,230,881 | | | | 170,218,914 | 523,449,795 |

* Not Available
** Dolmage (1922), GSC Summary Report, Part A
*** Hanson (1935), GSC Memoir #175

figure 5A-A' is a geological cross-section taken from figure 5. Figure 7 is a detailed map of the underground geology at the Double Ed and, together with figures 5, 5A-A' and 6, forms the basis of all geological interpretations of the deposit present in this dissertation. These figures are also located in the pocket at the back of this thesis. The surface geology of the Bonanza mine is presented in figure 8; figures 8A-A' and 8B-B' (in pocket) are a longitudinal-section and a cross-section through the deposit. Figures 3 through 8, inclusive, were drawn from the writer's own field observations and from a compilation of mapping and diamond drill logs recorded by the Granby Company and Cominco Limited. Geological information from the Granby operations was provided mainly by Bancroft (1918) and Nelson (1935); the majority of the Cominco work was performed by D. W. Heddle, F. D. Gill, and M. J. Osatenko, and is found in unpublished company reports and maps. The small scale used for the maps resulted in large figures that show the rather intricate details of the deposits.

The geological setting of the deposits is discussed in Chapters III, IV, and V. The Hidden Creek mine was the major copper producer in the area, consequently is of most economic interest. Both the Bonanza and Double Ed deposits are much smaller than the Hidden Creek deposit, but all three have similar host rocks and sulfide mineralogy. The Hidden Creek and Bonanza deposits were nearly mined out, but the Double Ed deposit is intact. Work carried out after the mine closed has provided abundant information about all three of the deposits. Because this information is available, a comparison between them and

other volcanogenic massive sulfide deposits in British Columbia (see figure 9 in pocket) and the rest of the world is possible.

This thesis utilizes previously gathered information and incorporates the writer's mapping, research data and observations into a framework which attempts to establish the volcanogenic nature of the cupriferous massive sulfide deposits at Anyox.

# CHAPTER II

# REGIONAL GEOLOGY

The geology of the Anyox area was first mapped by McConnell (1912) and later by Dolmage (1922), both officers of the Geological Survey of Canada. Nelson (1935) published a summary of the geology around the Hidden Creek and Bonanza mines, plus a brief description of the regional geology. A geological compilation map of the Stewart, Anyox, Alice Arm, and Terrace areas was published by Carter and Grove (1972). Current geological work covered by the writer in this thesis is shown in figure 2 and figure 3 (in pocket), which depict the regional geology of the Anyox area on scales of 1:250,000 and 1:24,000, respectively. The regional geological setting of the Anyox area is covered in this chapter; detailed geology and geochemistry around the Hidden Creek, Double Ed and Bonanza deposits are discussed in Chapters III to VII, inclusive.

## STRATIFIED ROCKS

### General Stratigraphy

The metamorphosed stratified rocks in the Anyox area are composed of pillowed basaltic lava flows which are conformably overlain by fine-grained clastic sedimentary rocks (figure 10 shows a composite columnar section of the Anyox stratigraphy). The entire volcanic-sedimentary

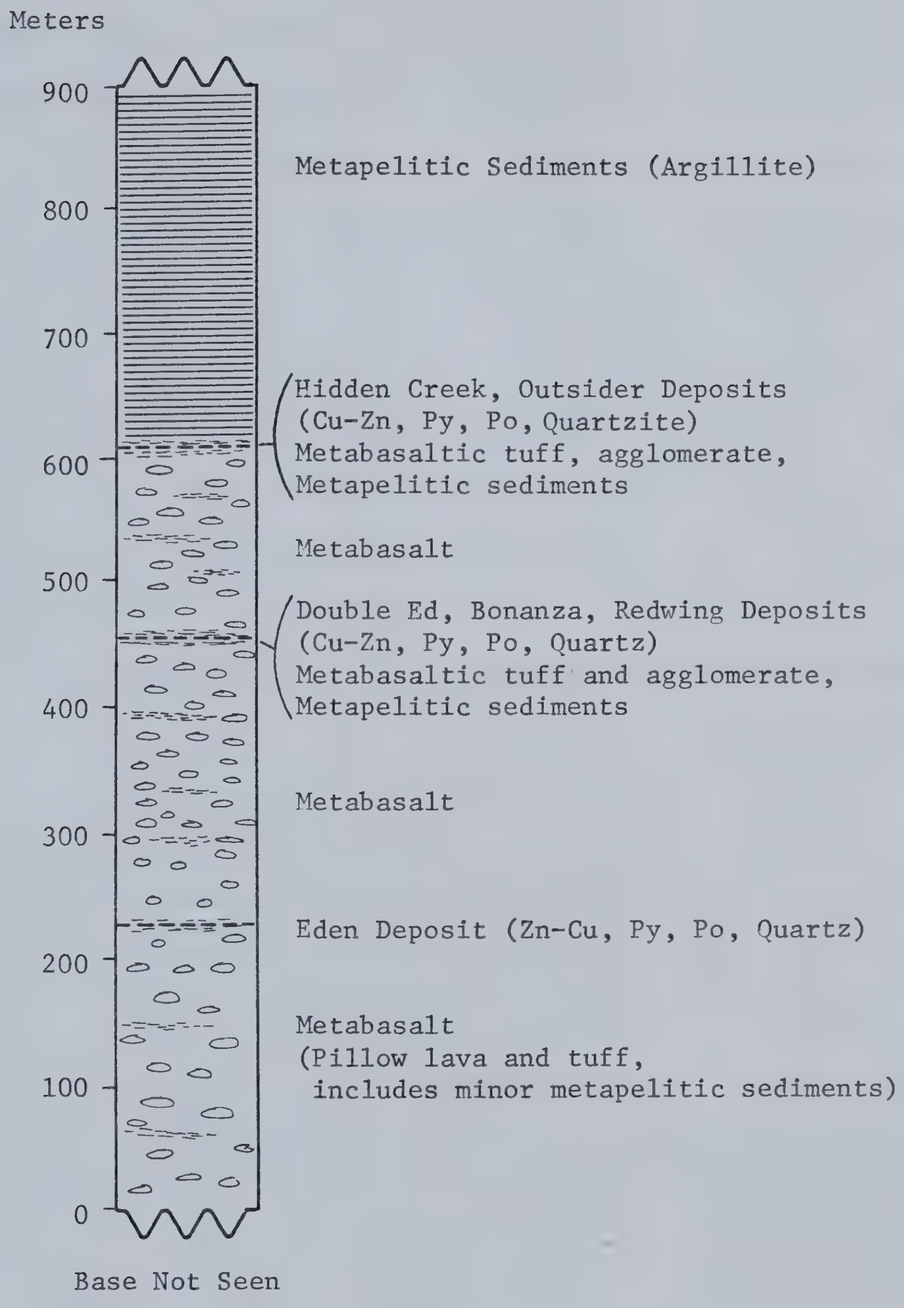



Figure 10. Composite Stratigraphic Column of the Mesozoic age Rocks in the Anyox area.

assemblage forms a roof pendant within the Coast Range Intrusive Complex. Regional thermal metamorphism of greenschist grade has affected both the volcanic and sedimentary rocks in the Anyox pendant.

The metabasaltic rocks are of a uniform tholeiitic composition and were extruded in a submarine environment. The metavolcanic rocks are genetically related to the copper deposits in the area and for this reason have been studied more than the metasedimentary rocks. Metasedimentary strata of quartzite and carbonaceous phyllite are directly associated with the sulfide depositional environments, while metapelite and quartzo-feldspathic metasedimentary rocks form a thick capping sequence over the entire volcanic pile. Figure 3 illustrates the subdivisions of the stratified rocks mappable on a regional scale.

## Metabasaltic Rocks

### 1. Age and Correlation

The metavolcanic rocks of the Anyox area form a thick succession of pillowed tholeiitic basalt with subordinate pyroclastic layers and lenses. A thick sequence of metasedimentary rocks overlies and is locally interbedded with the metavolcanic pile. Previous regional mapping has treated the Anyox area only on a cursory scale and was designed to correlate the strata at Anyox with the formations present near Stewart or Alice Arm, British Columbia. McConnell (1912) and Dolmage (1922) both assigned the rocks in the Anyox pendant to the Bear River Formation, but the name was later changed to the "Hazelton Group" by Hanson (1925). Grove's work (1971) in the Stewart map area, and Tipper and Richard's (1976) data on the Hazelton Formation show

that it is typically a submarine to subaerial assemblage of calc-alkaline basaltic to rhyolitic rocks. The upper Triassic Karmutsen formation exposed on the Queen Charlotte Islands was studied by Sutherland Brown (1968) and found to consist of pillowed metabasaltic lava. In figure 11, a composite columnar section of the volcanic-sedimentary strata at Anyox is compared to a columnar section for the Karmutsen-Yakoun formations on the Queen Charlotte Islands. The rocks at Anyox are tentatively correlated with the Karmutsen formation by the writer, therefore are considered to be upper Triassic in age. This correlation is further discussed in Chapter VIII under the section, "Tectonic Setting of Ore Deposits".

2. Pillow Lava

Most of the lava flows exposed in the Anyox pendant show well-developed pillow structures. The pillows range in size from a few centimeters to over 2 m in diameter. Selvages are usually 1 to 2 cm thick and are no longer glassy, but much finer grained than the metabasalt in the pillow centers. Radial fractures extending outwards from the pillow centers are occasionally found and may be remnants of original cooling cracks in the lava. Lava tubes occur with the pillowed masses and, although similar to the pillows, are identifiable by small rectangular quartz fillings (5 to 10 cm long), which occur in the center of the tube. Dikes with compositions identical to the pillows cross-cut the volcanic pile and are remnants of feeder systems which fed overlying lava flows.

The rock type making up the pillowed lavas has been identified as a tholeiitic metabasalt (see Chapter VI). Textures in the pillows

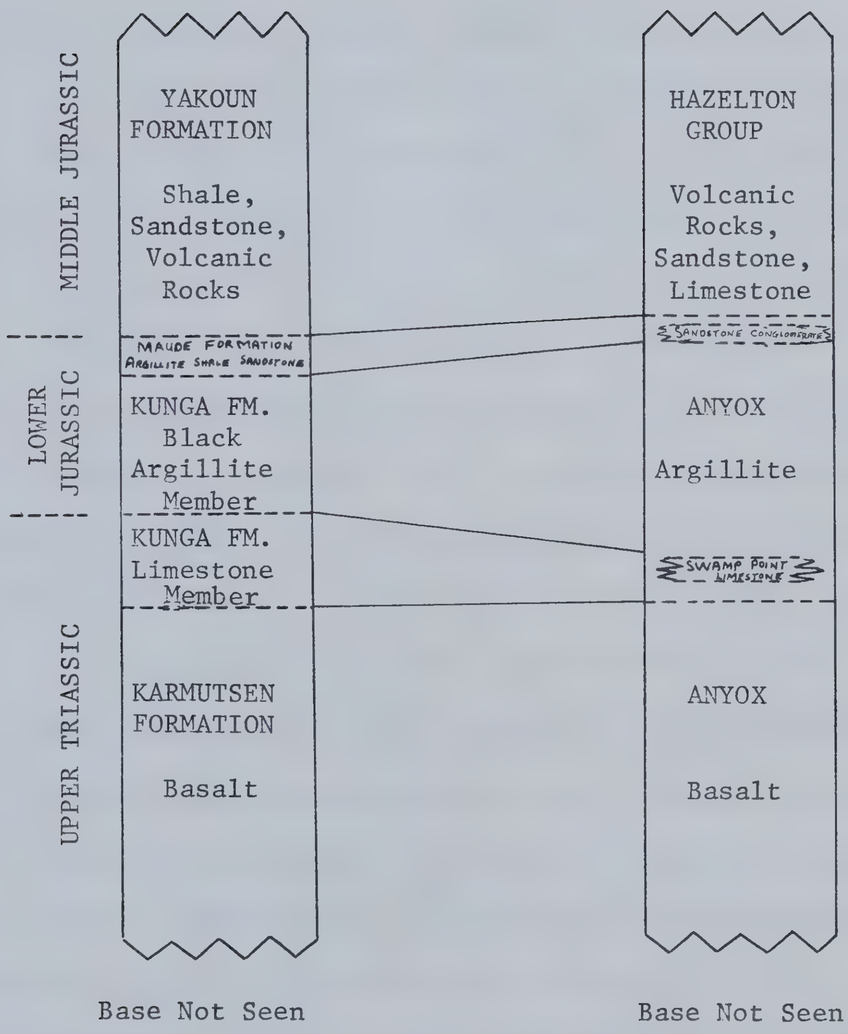



Figure 11. Comparison of Triassic-Jurassic Portions of the Anyox and Queen Charlotte Islands Stratigraphic Columns (after Sutherland Brown, 1968).

range from fine to coarse-grained and are often porphyritic. The mineralogy of the rocks reflects the greenschist grade of metamorphism; occasionally relict minerals such as hornblende or labradorite are observable in thin section. The groundmass of the lava is typically composed of: actinolite, chlorite, biotite, sericite, calcite and albite. The primary flow alignment of the minerals is weakly preserved, visible in thin section. The phenocrysts seen in many hand samples and outcrops are relict labradorite crystals which have been extensively saussuritized and are now assemblages of albite, zoisite, sericite and calcite. A similar saussuritization occurs in the groundmass plagioclase crystals, but is very fine-grained. Porphyroblasts of clinozoisite and albite appear as radiating tabular crystals in thin section, and as rounded white blebs 1 to 2 mm in diameter in hand specimen. Quartz veins several millimeters in width cut some thin sections and contain albite, pyrrhotite and chalcopyrite. Quartz veining is more common in the altered zones, as is chloritization and sulfide enrichment (see the section concerning alteration later in this chapter). Other accessory minerals are magnetite, ilmenite, and maghemite, identified in some polished thin sections. Magnetite is usually present in only trace amounts, but may reach 3% in some altered rocks.

The pillow structures have been only weakly deformed in most places. Tectonic deformation consists of a flattening and elongation of the pillows, and in some areas has been intense enough to cause fragmentation. Deformation of the pillowed masses while they were still plastic is visible in some localities and is best seen in the large, bulbous pillows (1 m in diameter) exposed in outcrops several hundred meters

southeast of the Double Ed deposit.

3. Interpillow Space Fillings

Hollow spaces between the pillows have been filled by siliceous material or fragments of selvages. The siliceous fillings are mostly quartz with minor epidote, albite, calcite and chlorite. Some epidote and albite-rich space fillings are present, especially in outcrops 750 m southeast of the upper dam on Falls Creek. This siliceous type of interpillow space filling was formed after the extrusion of the pillows, but the epidote-albite-rich space filling also forms a matrix in which some pillows and pyroclastic debris are suspended. The siliceous material most likely originated as a precipitate from solutions percolating through the newly-formed volcanic pile, while the epidote-albite material reflects a volcanowacke mud accumulated from seafloor weathering of the basalt. Pyrite, pyrrhotite and chalcopyrite often accompany the interpillow material. The sulfides usually appear as scattered grains in trace amounts, but also form clusters up to 5 cm in diameter. Enrichment of sulfides in interpillow space fillings is a positive indication of nearby massive sulfide mineralization. Sulfide enrichments are associated with both the Double Ed and Hidden Creek deposits as interpillow space fillings in the footwall strata. Such zones of sulfide enrichment may be used as a prospecting tool because they indicate areas where ore-bearing hydrothermal solutions passed through the volcanic pile.

4. Fragmental Rocks

This category includes all rocks which have a fragmental texture but are not identifiable as pyroclastic in origin. Tectonic, explosion,

pillow and flow top breccias as well as volcaniclastic metasedimentary rocks all have a similar appearance and have been grouped together as one map unit in figures 3, 4, 5, 6, 7, and 8 (in pocket). A thin, limonitic stain on weathered surfaces is produced from the oxidation of the sulfide minerals. Fragmental rock outcrops contain angular to subrounded fragments of metabasalt and quartz which lie in a foliated matrix of chlorite and biotite. Most fragments are in contact with one another and are associated with only minor matrix material. Fragmental rock units are cut by quartz and calcite veinlets and stringers, which carry ½ to 1% pyrite and pyrrhotite, plus traces of chalcopyrite. Fragment size ranges from several millimeters to 20 cm. A strong preferred orientation of the fragments and matrix is usually present and reflects deformation by shearing. In many outcrops features of both volcaniclastic sedimentation and tectonic brecciation are present, and may represent shear deformation of an originally sedimentary rock mass. Deformed fragmental rocks are associated with the synclinal fold between Bonanza and Falls creeks and the anticlinal fold east of Lower Dam Lake. Strain relief by shear deformation was concentrated in the less competent tuffaceous and fragmental layers. Intact pillows are recognizable in some of the fragmental pyroclastic horizons because the deformation occurred primarily in the matrix material.

In the footwall of the Number 6 deposit at the Hidden Creek mine, a breccia composed of large basaltic fragments exists. Biotite, chlorite and quartz-rich veins heal the fractures. This breccia is believed to have been produced by an <u>insitu</u> fragmentation, most likely caused by a

volcanic explosion or subsidence of the newly erupted volcanic pile. Similar fracturing and veining does not appear to extend into the overlying sulfide-rich zone.

5. Pyroclastic Rocks

Layers and lenses of pyroclastic rocks are interbedded with the pillowed metabasalt throughout the metavolcanic pile. Shearing obliterated most primary features in the rock mass, but definite pyroclastic textures are observable. The most abundant pyroclastic material was originally tuffaceous, but shear deformation has destroyed most of the primary bedded textures; regional metamorphism and deformation have combined to produce a quartz-chlorite schist. Small, discontinuous lenses of lapilli and crystal tuff, as well as agglomerate, are locally preserved. Agglomerate occurs in the footwall of the Hidden Creek, Bonanza and Double Ed deposits; agglomerate and lapilli tuff beds also occur in the hanging wall and higher in the stratigraphic column at the Double Ed. The Bonanza deposit has metabasaltic crystal tuff in both the hanging wall and the footwall. A highly chloritic, quartz-veined and sulfide-rich rock unit, originally a basaltic tuff, completely surrounds the Number 2-3 deposit at the Hidden Creek mine (see figure 4). A thin lens of agglomerate also underlies the Number 2-3 deposit.

The pyroclastic rocks are composed of: chlorite, actinolite, albite, quartz, epidote, calcite, biotite, sericite, pyrite, pyrrhotite, chalcopyrite and magnetite. These rocks, especially the tuffaceous variety, most commonly occur as chlorite schists. Chlorite content varies from 20% to 75% and is related to the intensity of premetamorphic alteration, which is associated with hydrothermal convection systems

operative during the early stages following the formation of the volcanic pile. Pyrite, pyrrhotite and chalcopyrite occur as disseminations and streaks along the foliation planes of the chlorite schists; grades of up to 2% of these sulfide minerals occur locally. Non-volcanic sediment, interbedded with the pyroclastic layers, has been metamorphosed to quartzite bands and/or quartz-chlorite-biotite schist. Most inclusions of metasedimentary material are only several centimeters thick, but some form lenses 10 m thick and 50 m long. The pyroclastic layers are usually less than 30 m thick, have an average range between 3 and 7 m in thickness, and may be up to 500 m long.

6. Premetamorphic Alteration

Alteration of the basaltic lavas associated with the Hidden Creek, Bonanza and Double Ed deposits accompanied the formation of the cupriferous sulfide bodies. Although regional metamorphism and deformation have overprinted the alteration mineralogy, it has not been totally obscured. The most extensive alteration zone is associated with the Hidden Creek deposit, while smaller zones surround the Bonanza and Double Ed deposits.

The dominant features of the altered basalt are: chloritization, quartz veining, and impregnation of pyrite, pyrrhotite and chalcopyrite. Variations in the alteration intensity are recognizable in outcrop and in hand specimen, as well as mineralogically and geochemically. Chloritization of the basalt ranges from weak to intense; increasing chloritization of the rocks is usually accompanied by more abundant quartz veining and sulfide (pyrite, pyrrhotite and chalcopyrite) content. Because of their areal extent, the alteration features in the metabasalt

are better seen at the Hidden Creek deposit than at the Bonanza and Double Ed deposits where the altered zones are smaller and internal relationships within the zones are complicated by faulting and folding.

Quartz veining takes the form of thin, "feathery" quartz stringers cross-cutting the metabasalt pillows. The veins are discontinuous, measure between 1 mm and 1 cm in width, and range from 10 to 20 cm in length. The veins are also deformed, which indicates that they developed prior to the latest phase of folding, therefore may be related to the hydrothermal alteration processes active within the original basaltic pile. Traces to several percent of pyrite, pyrrhotite and chalcopyrite are associated with the quartz veins.

The chloritization, quartz veining and sulfide enrichment are attributed to the processes of hydrothermal alteration which acted on the basaltic lavas, following their extrusion onto the sea floor. Circulating hydrothermal fluids affected the lavas and the rocks now show a trend of decreasing alteration away from the sulfide deposits. Relatively unaltered metabasalt occurs near the sulfide bodies, suggesting that the hydrothermal solutions were not pervasive, but were restricted to specific zones or channelways. A more detailed description of the alteration zones, as well as geological and geochemical trends, will be discussed in the following chapters.

### Metasedimentary Rocks

1. Quartzite (Metachert)

Thin to thick beds of white laminated quartzite lie along the main volcanic-sedimentary contact in the Anyox pendant. The quartzite is a

recrystallized cherty sediment layer and varies from a pure quartzose rock to an impure variety that contains biotite, chlorite and graphite. These beds are absent in many places along the contact; in other localities they occur as clasts, which are incorporated into fragmental zones composed of volcaniclastic debris formed during erosion of the volcanic pile. Bed thickness varies from several centimeters to over 1 m.

An anomalously thick accumulation of quartzite is associated with the Hidden Creek massive sulfide deposit, where bed thickness reaches 75 m. Pyrite, pyrrhotite, chalcopyrite and sphalerite bands or massive layers occur throughout the siliceous horizon; small calcareous lenses and metapelitic and metabasaltic tuff beds are interbedded with the quartzite-massive sulfide layers. A significant feldspar and mica content is visible in both hand samples and thin sections and is reflected in the alumina and potassium contents of the strata. The quartzite beds vary from pure to impure and in some layers represent quartzo-feldspathic sediment. The quartzite layer is unrelated to felsic volcanism because it is texturally a fine-grained sedimentary rock. In addition, it shows no flow textures, quartz eyes, or fragments, and there is no recognizable volcanic source nearby to generate a felsic lava, tuff or tuffite.

Two possible sources for the silica in the quartzite beds are the volcanic pile and seawater. Hydrothermal alteration (chloritization, saussuritization) of the basaltic rocks would release silica into the marine environment near the hydrothermal vents. The silica in solution would then precipitate near the vent areas. A "bloom" of marine life around the hydrothermal vents would also cause a significant amount of fine-grained siliceous debris to accumulate on the surrounding sea floor.

Wise and Weaver (1974) and Garrison (1974) point out that deep sea cherts form from organic detritus rather than exhalative precipitates from hydrothermal solutions. Their argument may well apply to all areas except the mineralized hydrothermal vent localities. The vent areas differ from the bulk of the volcanic pile in the intensity and extent of their rock alteration; these vent areas also contain large amounts of chemical precipitates (the sulfide minerals). With the above factors in mind, it is most likely that the silica in the quartzite layers originated as a chemical precipitate from hydrothermal solutions exhaled from the volcanic pile. The importance of the organic component of the quartzite beds is also recognized, but is subordinate to the chemical component.

2. Cupriferous Sulfide Bodies

Three significant deposits of cupriferous pyrite and pyrrhotite in the Anyox area have been studied by the writer. The Hidden Creek, Bonanza, and Double Ed deposits are composed of massive sulfide beds and lenses which contain up to 10% copper, but average 1.5% copper in the composite sulfide body (Grove, 1965, British Columbia Ministry of Energy, Mines and Petroleum Resources, 1979, "Minfile"). Chalcopyrite is the copper-bearing phase in all three deposits; it contained trace values (0.01 Troy ounces per Ton) of gold recovered during mining by the Granby Company. Sphalerite, a minor economic sulfide mineral in the deposits, occurs in thin, discontinuous beds and lenses; no data is available on zinc grades in the Hidden Creek and Bonanza mines, but 0.6% zinc is contained in the Double Ed deposit (British Columbia Ministry of Energy, Mines and Petroleum Resources, 1979, "Minfile"). Pyrite is more abundant than pyrrhotite, particularly in the siliceous

sections of the mineralized strata.

Metabasaltic lava and tuff enclose the Double Ed, Bonanza, and the Hidden Creek Number 2-3 deposits. The main massive sulfide deposits at the Hidden Creek are interbedded with siliceous metasediment (quartzite), and in the stratigraphic upper layers with carbonaceous phyllite and argillite. A low grade (<0.5% Cu) stringer sulfide zone cross-cuts pillowed and tuffaceous metabasalt underlying part of the Hidden Creek deposit. In the Bonanza and Double Ed deposits, layers of metamorphosed sedimentary material (chert, shale, basaltic tuffite) are abundantly interbedded throughout the sulfide zone, but the layers are thin and discontinuous. Several stratiform layers or pods of barren pyrite overlie the Hidden Creek deposit and are interbedded with the argillite.

Structural deformation imparted a foliation to the micaceous gangue minerals in the sulfide deposits. The deformation also caused recrystallization and coarsening of sulfide grains, plus plastic deformation of chalcopyrite and brecciation of pyrite and sphalerite. The sulfide bodies were folded, locally overturned, and faulted at the Hidden Creek deposit; at the Double Ed they were folded into a steeply plunging chute; at the Bonanza, the ore body was tilted and truncated by a major thrust fault.

3. Carbonaceous Phyllite

Black carbonaceous phyllitic rocks are exposed in the south wall of the Number 1 glory hole at the Hidden Creek mine (see figure 4). Mining has removed a portion of the rock unit, but original thickness was about 5 m. Carbonaceous rocks may have capped all deposits at

Hidden Creek, with the exception of the Number 2-3 deposit, but mining has removed much of the material. If present exposures in the glory hole walls are indicative, the carbonaceous layer is restricted to the vicinity of the Number 1 deposit. Carbonaceous and graphitic schist phyllite are interbedded with the argillite above the Number 6 deposit and occur along the volcanic-sedimentary contact between Hidden Creek mine and Bonanza Creek. The interbedded carbonaceous units are 15 to 30 cm thick and do not form laterally extensive beds, but occur sporadically up to 300 m above the contact.

The carbonaceous phyllite at the Hidden Creek mine is mineralized, with up to 2% chalcopyrite and 3% pyrrhotite-pyrite. The sulfide mineralization occurs in blebs along foliation planes and in cross-cutting quartz veinlets. Many veinlets have been distorted, indicating a pre-deformational origin. The mineralogy of the phyllite is biotite, chlorite, sericite, and quartz grains, with 5 to 10% black carbonaceous matter. Copper grades were high enough to warrant mining the stratigraphically lower section of the carbonaceous unit, which indicates a gradational character between it and the underlying massive sulfide beds. The Bonanza and Double Ed deposits have no carbonaceous matter associated with the sulfide zones.

4. Argillite

A thick assemblage of metamorphosed sedimentary rocks overlies the metabasaltic volcanic pile on the east side of the Anyox pendant. The metasedimentary rocks were first mapped by McConnell (1912), who named them the "Goose Bay Formation". Dolmage (1922) correlated these rocks with the Kitsault River Formation near Alice Arm, as defined by

Hanson (1921); Hanson (1935) later abandoned the name and included this formation with the Hazelton Group. Grove and Carter (1972) also included the Anyox metasedimentary rocks in the Hazelton group. No fossil dates have been made on the metasedimentary strata but lithological similarities, especially between the associated metavolcanic rocks, suggest a closer correlation with the Karmutsen-Maude formations (Sutherland Brown, 1968) rather than the Hazelton formation (Tipper and Richards, 1976).

The metasedimentary rocks have been termed "argillite" in previous descriptions (McConnell, 1912; Dolmage, 1922; Nelson, 1935). The argillite is composed of repetitively interbedded quartzo-feldspathic siltstone and slate, phyllite or schist (where strongly foliated). The composite thickness of the argillite rock unit is over 500 m; in this interval individual bed thickness averages 20 cm, but ranges between 2 cm and 1.5 m. Rare beds of black-colored, impure limestone up to 30 cm thick and laterally discontinuous, are interbedded with the argillite.

Graded bedding is present in some of the siliceous siltstone layers where white weathering clastic grains stand out in a grey to black siliceous matrix. An overall graded bedding between the siltstone and shale beds probably exists, but folding and shearing of the layers has removed much evidence of this. The rocks are clastic sediments (flysch) deposited by turbidity currents in an oceanic basin near an active eugeosyncline. The direction of sedimentation is uncertain, but rip-up clasts of black limestone and siltstone near the Double Ed deposit indicate a northerly source. The source of the detritus was not the underlying volcanic pile and was distal to the site of sedimentation.

The quartzo-feldspathic siltstone is composed of fine-grained quartz, plagioclase, orthoclase, biotite, chlorite and traces of actinolite, sphene, rutile, pyrite and pyrrhotite. Carbonaceous matter is disseminated throughout the rock, giving it a black to grey color. The shale, phyllite or schist beds have been grouped under the category "metapelite", indicating a common original rock type which has undergone varying degrees of foliation. The metapelite contains fine-grained quartz, biotite, chlorite, actinolite, and may have up to 5% carbonaceous matter. Both the siltstone and the metapelite beds contain fine grains of pyrite and pyrrhotite, distributed evenly throughout and ranging up to 2%, but averaging less than ½% in abundance. Oxidation of the sulfides produces a weak to strong limonitic (red-yellow) stain on weathered outcrops. Upon weathering, the more resistant siliceous beds stand out as a series of ribs on an outcrop surface, while the metapelitic beds occupy the narrow depressions between the ribs.

500 m above the volcanic-sedimentary contact, the metasediments become distinctly more shaly and contain significantly fewer quartzo-feldspathic beds. Approximately 2.7 km east of the Hidden Creek deposit, coarse feldspathic sandstone beds outcrop. These are 2.5 to 3 m thick, separated by thin beds of metapelite and aggregate up to 90 m in thickness (Bancroft, 1918).

The depositional environment of the sediments was a submarine basin that was slightly reducing. A thick wedge of clastic eugeosynclinal sediments, derived from a distal source to the north, was deposited in the basin. Much later the sedimentation conditions became

more active, with the accumulation of coarse sandstone indicating uplift to the east and a migration of the source area towards the west.

### Quaternary Sediments

Glacial till and outwash consisting of clay, sand, pebbles, and boulders mantle the lower mountain slopes and floors of the valleys. The weight of the Cordilleran ice sheet depressed the land surface several hundred feet below sea level and resulted in recent marine sedimentation covering the lower portions of the valleys. Stratified marine clays underlie the Hidden Creek valley floor over 915 m north from Granby Bay. Bancroft (1918) identified fossils in this unit that are the same species as those presently living in Granby Bay. The land mass near the ocean rose between 45 and 60 m after the retreat of the ice sheet that covered the area.

The thickest accumulation of glacial till lies on the mountain slopes at elevations between 150 and 245 m. Ridge and mountain tops are bare rock covered in many places with snow or ice. Stream sediments are thick along the upper portions of Falls and West Bonanza Creeks. Fan-shaped deltas have developed at the mouths of Bonanza, Falls, and Tauw Creeks, but slag has obscured the delta at Falls Creek.

### Recent Sedimentation and Gossan Development

Weathering of the iron-rich sulfide deposits has produced notable gossans and well-cemented recent conglomerate. The gossans associated with the sulfide deposits are approximately 1 m thick where undisturbed by mining or trenching. The rock is composed mainly of limonite and minor hematite, which forms crusts and acts to cement fragments of

other rocks. Well-cemented outcrops as young as forty years old are present and contain recent fossils and mining equipment (rails, spikes, wheels).

## INTRUSIVE ROCKS

The oldest recognizable intrusive rocks in the Anyox area have a metagabbroic composition and are related to basaltic volcanism. Amphibolite stocks, sills and dikes intrude into all stratified rocks (except glacial debris). Other types of dikes are diorite, felsite, and lamprophyre. Granodiorite dikes and plugs occur throughout the area. The Anyox pendant lies within granodiorite rocks of the Coast Range Plutonic Complex.

### Metagabbro

Metamorphosed gabbroic rocks, ranging from fine to coarse-grained, intrude the pillowed metabasalt as dikes and sills. These rocks are restricted to the volcanic pile and do not intrude the overlying metasedimentary strata. The gabbroic intrusives are small bodies and are not extensive. Their form is one of a feeder system for overlying lava flows and does not resemble the "sheeted dike complex" associated with ophiolite bodies.

### Amphibolite

Amphibolite intrusive rocks occur throughout the Anyox pendant as plugs, dikes and sills. The amphibolite is composed of medium to coarse-grained hornblende, actinolite, chlorite, biotite and sodic plagioclase minerals. Contacts with surrounding rocks are sharp.

An amphibolite plug disrupts the mineralized zone at the Double Ed. A large intrusive mass of amphibolite is visible in adit walls and underground drill core, but at the surface the same body forms a sill-like intrusion along the volcanic-sedimentary contact. Northwest of Hidden Creek, amphibolite plugs and sills occur in the volcanic pile.

### Diorite

Diorite occurs as dikes throughout the Anyox area. The dikes have a northeasterly strike, show sharp contacts and vary from ½ to 10 m in width. Grain size varies from fine to medium and some dikes carry abundant biotite. The biotite-diorite dikes are cut by a non-biotite-bearing diorite phase. Faults truncate and displace both types of diorite. Woodcock and Carter (1976) dated a biotite schist adjacent to a diorite dike at the Bonanza mine and obtained a Tertiary (33 million years) age.

### Felsite

Several felsite dikes that cut the Double Ed deposit have been mapped. Others lie east of Lower Dam Lake and north of Hidden Creek (see figure 3 in pocket). The dikes are composed of porphyritic feldspar crystals in a fine-grained groundmass. Quartz is present in some dikes but is not ubiquitous. The dikes are 1 to 3 m in diameter and are often traceable for several kilometers. Elliott et. al. (1976) described similar felsite dikes in Alaska, 30 km west of Anyox; they are associated with felsic stocks.

### Granodiorite

Granodiorite stocks associated with the Coast Plutonic Complex occur in two localities in the map area of figure 3 (in pocket). Overburden obscures many contacts, but further south and west of the map area they are highly foliated and show considerable migmatization (Freeze, 1951). Large granodiorite intrusive bodies lie north and south of the metavolcanic-metasedimentary assemblage at Anyox. East of Observatory Inlet and west of Portland Canal, related granodiorite rocks outcrop extensively (Hanson, 1935). Grove and Carter (1972) have assigned a Tertiary age to the Coast Plutonic Complex in the Alice Arm-Anyox area.

### Lamprophyre

Small lamprophyric dikes occur throughout the map area. Grove and Carter (1972) show a lamprophyric dike swarm passing through the Hidden Creek mine. The occurrence of lamprophyric dikes is more extensive than they mapped, and several such dike swarms may exist. Smith (1972) has described similar lamprophyric dikes in nearby southeastern Alaska.

## QUARTZ VEINS

Two types of quartz veining are present at Anyox. The first type is characterized by large white quartz veins ranging from ½ to 5 m in thickness and occurring only in the argillite lithology. These veins are often associated with folds or faults and sometimes carry fragments of wall rocks. They are usually barren, but some carry traces to

massive pods of pyrrhotite, sphalerite and galena. The veins in the argillite on the north end of Granby peninsula carry low values of gold, as do similar veins to the south (Nabob claims). The larger quartz veins in the area were quarried for use as silica flux in the blast furnaces in the smelter.

The second type of quartz veining is associated with the mineralized zones and is best developed in the argillite, while extending only weakly into the metabasalt. The most extensive example of such quartz veining is at the Hidden Creek deposit (figure 4). There, in the folded argillite stratigraphically above the sulfide zone, a large area contains veinlets that range from 1 mm to 30 cm, but average 2 mm in width and are rarely over 1 m long. Some larger veins of the first type mentioned occur in the quartz-veined zones in the argillite. The veins are white to brown and contain traces to 2% pyrite or pyrrhotite and occasionally galena and spahlerite. The veins cross-cut bedding and foliation, often at sharp angles; they are most numerous in the folded strata closest to the orebodies and decrease outward from them. These features indicate that the veins formed after the sediments were lithified and that their source is the siliceous beds associated with mineralization. Folding and tensile fracturing in dilatant zones formed sites for silica deposition, which explains the intense veining near the folded ore bodies.

## STRUCTURAL GEOLOGY

Figure 3 illustrates the main structural features associated with the mineral deposits studied in the Anyox area. The most intensively

studied feature is the volcanic-sedimentary contact, which has been well-explored and mapped since the turn of the century. Mining and exploratory diamond drilling have added much information concerning the behavior of the main contact downdip from the surface. Few marker beds exist in either the metavolcanic or metasedimentary strata, therefore structural correlations are difficult. Because it was massive and more competent, the metavolcanic strata deformed by faulting and shearing, whereas the metasedimentary strata deformed by folding.

The volcanic-sedimentary contact, as shown in figure 3, has a northerly trend across the eastern portion of the Anyox pendant and separates a large mass of tholeiitic metabasalt to the west from a thick succession of argillite to the east. A block of metabasalt is exposed in an anticline south of Bonanza Creek and west of Granby Bay. Dips along the contact are generally steep ($70^\circ$ to $90^\circ$) and in many places the contact is overturned. The contacts along the Bonanza anticline are shallow on the west side and moderate to steep on the east side. The most complex folding of the contact occurs near the Hidden Creek deposit where the metabasalt forms a narrow salient extending into the metasedimentary rocks. The salient is a northerly plunging asymmetrical anticline with an overturned east limb. A synclinal fold lies directly west of the Hidden Creek anticline. Two small folds in the contact exist, one to the east and one to the west of Lower Dam Lake. Vertical faults cut the contact along Hidden Creek and Falls Creek where the displacement has been right lateral. A large, normal fault truncates the northern portion of the Bonanza

anticline and Bonanza deposit. Vertical displacement is at least 150 m, while the horizontal component is over 365 m, with the movement of the hanging wall downwards in a northeasterly direction. The Falls Creek fault has the largest horizontal displacement, 1160 m.

Notable structural features not on the main volcanic-sedimentary contact are the broad synclinal fold in the metasedimentary rocks between the Double Ed and Bonanza deposits, as well as the structure of the two deposits themselves. The mineralization at each deposit has a stratiform character, hence may be used as a marker horizon in structural reconstructions. The Bonanza deposit has the form of a gently plunging pipe-like body, while the Double Ed is pipe-like but has been folded and is steeply plunging. The Hidden Creek orebodies are on the main contact and are vertically dipping to overturned. Additional structural features of the deposits are discussed in Chapters III, IV and V.

A distinctive foliation has been imparted to most rocks by the deformational event. Tuffaceous zones in the volcanic pile have undergone shear deformation and are present mainly as chlorite schist. The pelitic component of the metasedimentary strata is present as a fine-grained biotite schist, while the quartzo-feldspathic siltstone is largely unfoliated. Two phases of deformation are suggested by the foliation directions in some outcrops where an earlier weak foliation has been overprinted by a stronger one.

## GEOLOGICAL SETTING OF ORE DEPOSITION

The cupriferous massive sulfide deposits at Anyox formed on an ancient sea floor and are genetically linked to the volcanic processes

active at that time. The regional geology indicates that during the Mesozoic era, volcanism in a deep ocean basin produced a thick pile of pillowed basalt flows. Volcanism occurred near a plate margin, but absence of ultramafic rocks suggests that the assemblage is not ophiolitic. The sedimentation conditions were deep water, slightly reducing, and distal from the source of the sediments. Continued sedimentation produced a thick (greater than 1200 m) assemblage of fine clastic sediments (laid down by turbidity currents), deep water chert layers, and carbonaceous pelite. The massive sulfide deposits formed during breaks in volcanism, especially during the late stage in the development of the basaltic pile. The largest and highest grade copper deposits occur at the volcanic-sedimentary contact (Hidden Creek deposit). All of the deposits show a sedimentary character, include metamorphosed sedimentary rocks, and have undergone the same deformation as their host rocks. Pyroclastic rocks and large to small alteration zones stratigraphically underlie all deposits studied at Anyox. The above features are indicative of a mineralizing event syngenetic with volcanism and sedimentation. Hydrothermal convection systems circulated seawater through the volcanic pile and vented metalliferous brines, which gathered in nearby depressions on the sea floor as metalliferous mud and sulfide layers. The mineralizing process was stopped either by the resumption of volcanism (as at the Double Ed), or by the sealing off of the system by clastic sedimentary debris, as at Hidden Creek. In the Late Triassic period, basaltic volcanism in an ocean basin along western North America gave rise to the Anyox massive sulfide deposits. Further discussion on ore genesis and geological setting is given in Chapter VII.

## SUMMARY

The oldest rocks in the Anyox area are pillowed metabasalt which accumulated in a back-arc ocean basin. The metavolcanic-metasedimentary assemblage forming the Anyox pendant has been correlated with the Upper Triassic Karmutsen-Maude formations on the Queen Charlotte Islands. The metasedimentary rocks continue eastward and are overlain by the Hazelton Formation in the Alice Arm area.

Cupriferous massive sulfide deposits with a stratiform character lie conformably in the metabasalt and argillite in the Anyox pendant. Economic sulfides are chalcopyrite and sphalerite with pyrite, pyrrhotite, and quartz forming the most common gangue minerals. Mining operations between 1914 and 1935 removed much of the cupriferous massive sulfide in the Hidden Creek and Bonanza deposits. The Double Ed, Eden, and Redwing deposits are intact but do not contain sufficient tonnage or grade to warrant mining at present.

The geological history of the area started in the Triassic period when a sequence of tholeiitic basalt was erupted onto the floor of an ocean basin. A thick pile of pillowed basalt built up in the basin and cupriferous sulfide deposits formed during the late and terminal stages of volcanic activity. During the Late Triassic to middle Jurassic periods, a thick assemblage of fine-grained eugeosynclinal clastic sediments accumulated in the ocean basin, which was reducing. In the Jurassic and Cretaceous periods, marine to subaerial volcanic and sedimentary rocks accumulated in the area. Intrusion of the Coast Plutonic Complex occurred in the early Tertiary period. Uplift and

unroofing of the Coast range batholiths has continued to the present day. Major tectonic displacements of fault blocks may have occurred during the Jurassic-Cretaceous periods, but is not well-documented at present.

# CHAPTER III

## THE HIDDEN CREEK DEPOSIT

The Hidden Creek Mine lies 2 km north of tidewater at Anyox. This copper deposit was the main source of ore supplied to the smelting complex near the townsite. The Granby Consolidated Mining, Smelting and Power Company Limited operated the mine from 1914 to 1935. The mine was closed down in 1935 because low world copper prices, high operating expenses and a decline in the millhead grades made the operation uneconomic. The British Columbia Ministry of Energy, Mines and Petroleum Resources, "Minfile" (1979), lists the remaining tonnage and grade as 18,144,000 tonnes of 0.46% copper. A substantial amount of the remaining copper mineralization is contained in a large zone of altered metabasalt, called the "stockwork deposit" in this thesis. Lower grade portions of the original tabular orebodies remain, and an undetermined quantity of low grade (below 1%) copper mineralization was developed on the -885 foot level prior to the mine's closure and flooding. Cominco Limited purchased the property in late 1935. The engineering and geological staff of Cominco decided it would be uneconomic to resume mining operations, but did continue to explore the area for new mineralization (Telfer, 1937). The stockwork sulfide zone was outlined in 1937 and a limited amount of underground development work was undertaken after re-opening the Granby +130 haulageway. No economic mineralization was discovered and the project was

abandoned. Later programs during the 1950s and 1960s tested the stockwork deposit and sections of the volcanic-sedimentary contact. The deposit still remains uneconomic to open.

A limited amount of information was published on the geology of the Hidden Creek mine during the 1914 to 1935 period. The principal articles describing the mine geology were published by McConnell (1912), Dolmage (1922), Nelson (1935), and Hanson (1935). J. A. Bancroft (1918) wrote an extensive private report to the Granby Company describing the geology of the Hidden Creek deposit. Whitmore (1952), Gilbert (1939), and Heddle (1964, 1968) of Cominco Limited carried out extensive geological investigations of the property during the 1936 to 1965 period. In 1976 M. J. Osatenko and the writer conducted geological exploration of the deposit for Cominco. Information on the subsurface geology was gathered by the writer from the publications listed above and old company records. Figure 4 is a composite geological map of the surface geology around the Hidden Creek mine; the map was modified after Osatenko (1977). Figures 4A-A' and 4B-B' are cross-sections through the deposits, modified after Nelson (1935).

The Hidden Creek deposit is the largest massive cupriferous sulfide body in the Anyox area. The deposit consists of three distinct types of mineralization. One is the stockwork zone which cross-cuts the altered metabasalt; the second is a series of massive sulfide lenses in a sheared and faulted metabasaltic tuff; the third is a series of tabular stratiform massive sulfide layers which conformably overlie the metabasaltic pile and grade into barren argillite. The deposits have a composite strike length of over 1.6 km and are known to extend

at least 500 m below the surface. The following sections describe the geology and structure of the Hidden Creek deposits; their geochemistry, sulfur isotopes and genesis are discussed in Chapters VI, VII and VIII, respectively.

## METABASALT

### Lithology

Pillowed metabasalt forms the lower portion of the stratigraphic column (figure 12) at the Hidden Creek deposit. The metabasalt is the metamorphosed product of an extensive series of submarine lava flows. The lavas have a tholeiitic composition (see Chapter VI) and were erupted onto the sea floor in a deep ocean basin. In addition to the pillow lavas, massive textureless flows (or sills), fragmental and pyroclastic lenses and layers are present. Dikes, which formed feeders to overlying lava flows, cross-cut pillows in several localities. Two trends are notable in the evolution of the volcanic pile. One is an increase in the volume of pyroclastic material (mostly tuffs) erupted in the late and terminal stages of volcanism; the second is a textural, but not compositional, change in the lava erupted (from coarse-grained and porphyritic to fine-grained at the end of volcanism). Weak to intense premetamorphic hydrothermal alteration has affected portions of the volcanic pile underlying the stratiform massive sulfide layers.

Pillowed lava flows are abundant throughout the entire volcanic pile. Pillow dimensions range between 30 and 45 cm in length and 20 to 35 cm in diameter. Spalls from the pillows are occasionally present and are several centimeters in diameter. Pillow selvages, several

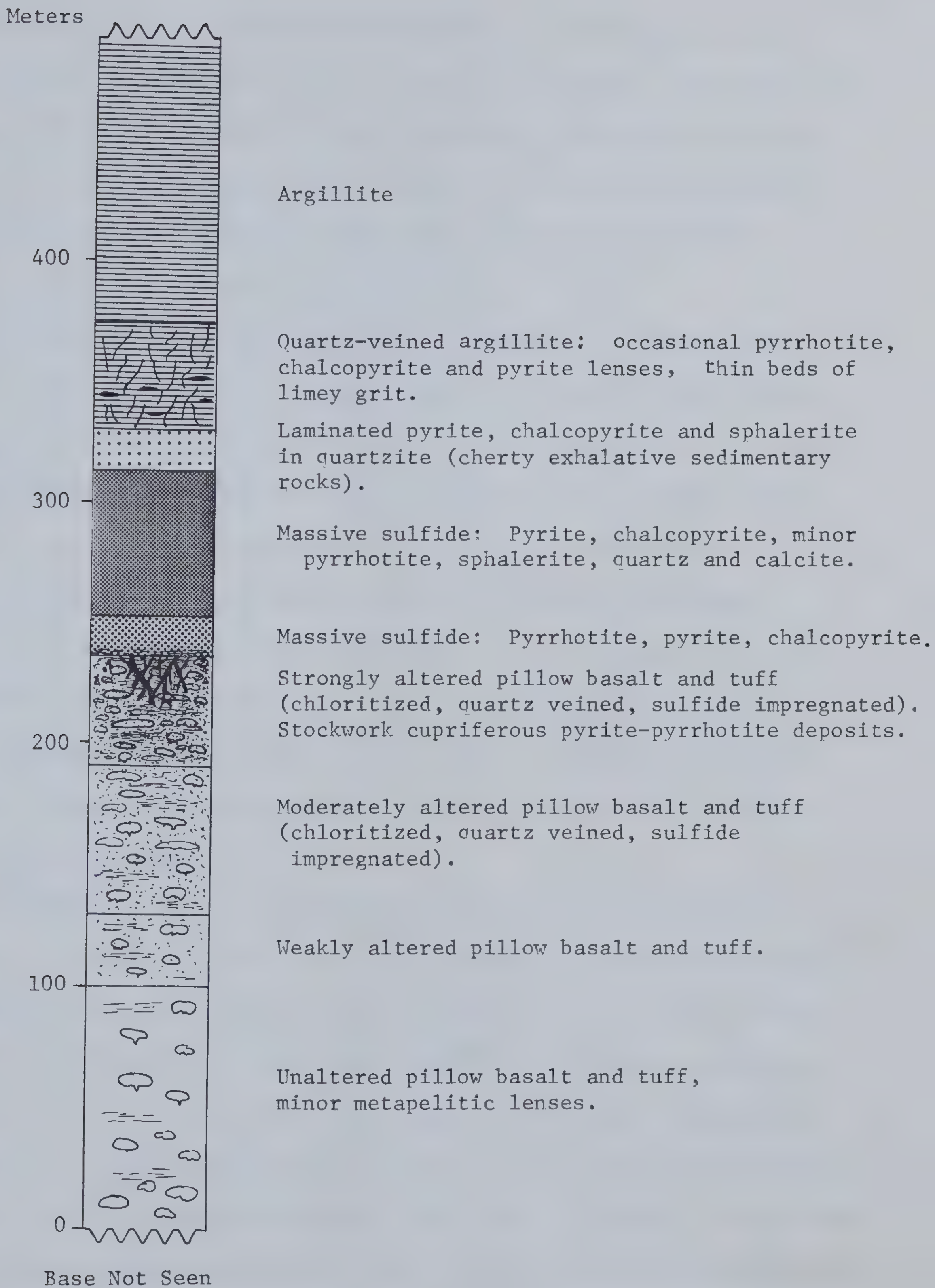



Figure 12. Composite stratigraphic column for the Hidden Creek Deposit.

centimeters thick, are prominent because they are finer-grained and more resistant to weathering than the rest of the pillow. Space fillings between pillows are composed of quartz, epidote, chlorite, biotite and calcite. In the alteration zones associated with the sulfide bodies, the interpillow space fillings often carry disseminated to massive clots of pyrite, pyrrhotite and chalcopyrite.

Pyroclastic layers and lenses occur throughout the stratigraphic column, but occur with more frequency near the massive sulfide bodies. Deformation of the tuffaceous layers has largely changed them to chlorite or actinolite-chlorite schist. The tuff horizons are laterally discontinuous and usually less than 2 m thick; however, the metabasalt enclosing the Number 2-3 deposit is a strongly altered tuffaceous horizon over 60 m thick locally. Streaks and bands of quartz, biotite or sulfides occur parallel to the foliation planes in the sheared tuff beds. Agglomerate beds occur locally but are not common. The bombs are tear-shaped or distorted chloritic masses which lie in an epidote to chlorite-rich matrix.

A fragmental zone in the metabasalt underlies part of the Number 6 deposit; this zone is composed of angular fragments ranging from several centimeters to 1 m in diameter. The fragments rest in a quartz-albite-chlorite-biotite matrix. While some fragments have been only slightly rotated after brecciation, others are completely foreign, suggesting a composite process of <u>insitu</u> brecciation and volcaniclastic or pyroclastic transport to their depositional site. The rocks are weakly albitized and mineralized. Other fragmental rocks are clearly recognized as pillow and flow top breccia, which consist of thin layers of pillow selvage fragments.

## Premetamorphic Alteration

Three alteration types have been recognized at Anyox. Silicification, chloritization and sulfide impregnation of the basaltic rocks were caused by the circulation of hydrothermal solutions through them. The intensity of each alteration type ranges from weak to strong. Figure 4 shows the distribution of alteration types and their intensity within the metabasalt around the Hidden Creek deposit. All of the rocks that stratigraphically underlie the sulfide bodies are altered to some degree.

Chloritization is the widespread alteration type. The chlorite now present in the rocks is a metamorphic mineral but reflects the alteration of the basalt prior to metamorphism. Chlorite is present in moderate amounts in the unaltered metabasaltic rocks throughout the area, but is distinctly enriched near the sulfide deposits. Chloritization is mappable in the field and is visible in hand specimen and thin section. The MgO values obtained from bulk rock geochemistry are high for chloritized rocks compared to values for unaltered rocks.

Silicification is mapped in the field on the basis of abundance of quartz veins and relative hardness of the rock. Two types of quartz veins are present; the most common type are tiny, thread-like veins 1 to 5 mm wide and 10 cm long, while the other variety are larger, 1 cm wide and over 30 cm long. The veins carry traces to abundant grains of pyrrhotite and chalcopyrite. Thin sections of the smaller veins show that they are composed of quartz and albite, sometimes with albite more abundant than quartz. Most of the quartz veins are deformed, which indicates that they were premetamorphic in origin. Rock geochemistry

does not show a strong silicification in the rock matrix containing abundant quartz veins, which indicates little silica introduction associated with the alteration and may mean the source of the quartz veins is the altered rocks themselves. The intensity of veining increases towards the sulfide bodies and is best seen on the west side of the 2-3 deposit.

Sulfide minerals are present in the altered rocks and increase in abundance with an increase in chloritization and quartz veining. Pyrrhotite predominates over pyrite, a relation which may be due to metamorphism of the original pyrite in a mafic-rich rock. Chalcopyrite s present with the pyrrhotite in most cases as exsolution blebs, but it does form discrete grains and massive clusters. The sulfides are disseminated throughout most of the unaltered lava in trace quantities, but show a marked increase in the more highly altered rocks. The presence of sulfides in the altered zones is shown by strong geochemical enrichments in iron, sulfur and copper. The sulfides occur in quartz veins, grains along foliation planes, massive clusters in interpillow space fillings or as sparse to abundant enrichments in altered lavas and tuffs.

The Number 2 and 3 deposits lie in a highly altered tuff which has been strongly chloritized, veined by quartz and impregnated with sulfides. The alteration pattern extends westward and weakens in intensity. The deposits are made up of lenses, bands and disseminations of chalcopyrite and pyrrhotite interbedded and surrounded by highly altered basaltic tuff and lava.

## SULFIDE DEPOSITS

The original "discovery" outcrop at the Hidden Creek mine became the Number 1 orebody. Additional prospecting and diamond drilling outlined eight massive sulfide bodies nearby. The Number 1,2,3 and 6 deposits outcropped or subcropped, while the Number 4 and 5 deposits were "blind" and were discovered by diamond drilling. Figure 4 shows the present geology near the orebodies, while figure 13 shows the original location of the deposits before mining. The mining of the orebodies has resulted in extensive surface subsidence, which has created steep-walled pits. The contacts drawn in figure 4 were deduced from remnants left unmined, old pillars and collapsed rubble. Subsidence and caving are continuing; large blocks of massive sulfide boulders are loose and shift easily, making any mapping in the pits both difficult and dangerous.

Three types of cupriferous sulfide deposits have been identified at the Hidden Creek mine. The most important type consists of a conformable tabular massive sulfide body that is interbedded with siliceous metasediments and occurs at the volcanic-sedimentary contact. The second type of deposit is made up of a series of massive sulfide lenses interbedded with highly altered basaltic tuff, and lies within the volcanic pile near the volcanic-sedimentary contact. The third deposit type was never mined, is of subeconomic importance and consists of a series of mineralized quartz veins and altered basalt which cross-cut the volcanic stratigraphy and underlie or are transitional into the other two types of deposits. All three deposit types are coeval and are related to the same mineralizing event; each will be dealt with separately in the following sections.

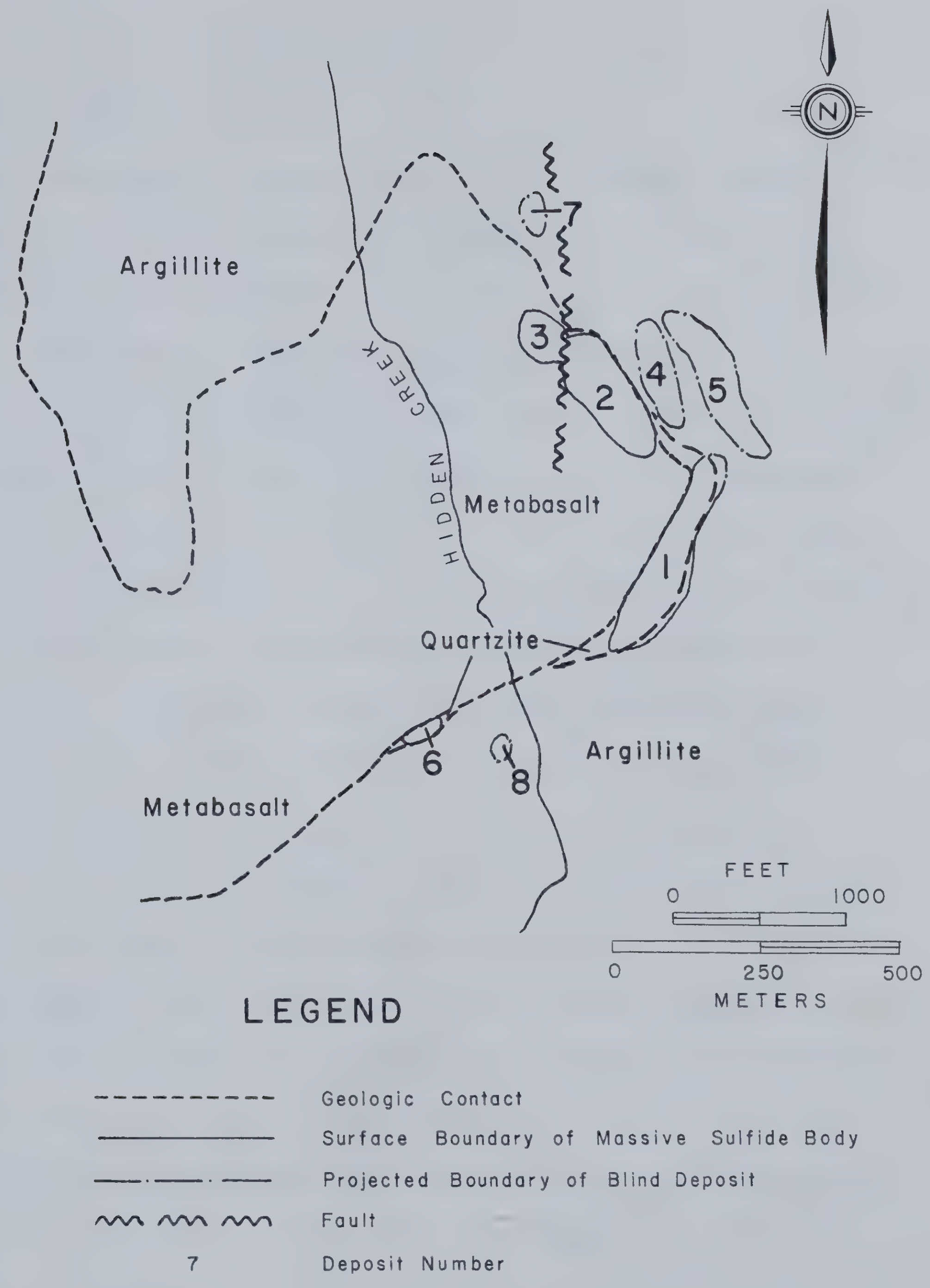



Figure 13. Location of massive sulfide deposits at Hidden Creek prior to mining (modified after Bancroft, 1918, and Nelson, 1935).

## Stratiform Sulfide Deposits

### 1. Form and Internal Features

Stratiform massive sulfide deposits occur along the volcanic-sedimentary contact and constituted the major source of ore during the life of the Hidden Creek mine. The stratiform orebodies (Number 1, 4, 5, 6, 7 and 8) have a tabular to elongate shape, are associated with cherty or siliceous metasedimentary rocks, and are conformable with the metavolcanic pile and the argillite sequence which stratigraphically overlies it. Deposits 1, 4, 5 and 6 are transitional from the metabasalt to the barren argillite. Vent areas where hydrothermal brines discharged onto the sea floor are associated with each stratiform sulfide deposit. The former fumaroles are marked by pyritic bodies which "extend as blunt wedges" into the metabasalt (Hanson, 1935). The metabasalt around the fumaroles is "silicified and sheared" (Nelson, 1935), indicative of hydrothermal alteration overprinted by structural deformation. Copper grades decreased at the fumarole and were sub-economic during mining operations. Near the fumaroles, lenses of massive chalcopyrite occupied rolls in the metavolcanic pile along the basal portions of the stratiform sulfide layer.

The majority of the stratiform layer is made up of disseminated to massive sulfide and quartzite. The layer reaches up to 75 m in thickness and extends over 1.6 km along the volcanic-sedimentary contact. The quartzite is a metamorphosed siliceous sinter which shows crude layering of pyrite crystals, and has undergone varying degrees of recrystallization. The quartzite is micro- to finely crystalline with a grain size that ranges from 2.0 to less than 0.1 mm. The pure quartzite

weathers grey to white, but is stained yellow to orange-brown where it contains pyrite grains. Sedimentary bands, several centimeters thick, of pelite, basaltic tuffite and quartzo-feldspathic silt occur throughout the quartzite layer and have been metamorphosed to biotite, chlorite, sericite, actinolite and quartz assemblages. Lenses and layers up to 10 m thick and 100 m long of highly altered metabasaltic tuff or argillite are interbedded with the quartzite. The massive sulfide zones grade laterally to barren quartzite, which usually contains scattered grains of pyrite in trace amounts. Lenses and layers of quartzite are interbedded with the massive sulfide bodies, which contain at least 2% fine interstitial quartz grains. The massive sulfide-quartzite layer is of a sedimentary origin, as evidenced by its conformable contacts with enclosing rocks and the interlayering of other sedimentary and volcanic rocks.

The stratigraphic upper contact between the massive sulfide-quartzite layer and the argillite is not sharp and in many cases is gradational. The amount of pelitic and quartzo-feldspathic metasedimentary rock increases upward near the stratigraphic top of the massive sulfide-quartzite layer, until the sulfide component is lost entirely in the metasedimentary pile which caps the mineralized zone. Small bodies of massive pyrite occur in the barren argillite overlying the mineralized horizon, but have no physical connection to the main sulfide deposits. Mining development revealed that the Number 1 and 5 orebodies extended into the argillite (Nelson, 1935), which indicates that sedimentation was active during the later stages of sulfide deposition. A bed of siliceous pyrite, 5 m thick, lies in barren argillite 50 m above the

main sulfide body at the Number 7 deposit. A small lens of sulfide, 5 m thick, is interbedded with argillite 183 m south of the volcanic-sedimentary contact along Hidden Creek (Bancroft, 1918). The significant interbedding of massive sulfide and barren argillite indicates that sulfide formation was active until it was literally smothered by clastic sediments. Such an influx of sediments may have sealed the recharge-discharge areas of the geothermal system, resulting in a shutdown of the sulfide-producing mechanism.

2. Mineralogy and Textures

Although the stratiform sulfide bodies have similar shapes and mineralogy, the volume and grade of each deposit is variable. The largest amount of ore grade material was contained in the Number 1 deposit, followed by the Number 5, 6 and 4 deposits. Deposit Numbers 7 and 8 were never mined because of their low grades (less than ½% copper); no reserves are known on these small deposits. The majority of the sulfide minerals making up the deposits are pyrite with subordinate pyrrhotite; these sulfides vary in relative proportions throughout the orebody, but show little evidence of zonation. Chalcopyrite and sphalerite are the economic sulfide minerals and occur as fine disseminations or as massive layers and lenses associated with the pyrite and pyrrhotite. All of the gold is carried by the chalcopyrite and none is associated with the pyrite. The chalcopyrite contains minor amounts of silver, which is also carried in the sphalerite. Typical grades during mining were 1.5% copper, 0.005 Troy ounces of gold per Ton, and 0.30 Troy ounces of silver per Ton (Nelson, 1935). The copper in the deposits came entirely from chalcopyrite which averaged 5% in most ore

blocks, but ran as high as 30% in some stopes. Sphalerite was smelted for its silver content, but zinc was not recovered. Sphalerite lenses up to 1 m thick and several meters long are found intercalated with the massive sulfide layers, but most commonly occur as fine disseminations in the quartz-pyrite-rich massive sulfide. Arsenopyrite blebs are present in some polished sections, but are rare. Gangue minerals not already mentioned are quartz, chlorite, actinolite, tremolite, calcite, biotite, sericite and magnetite. Actinolite, biotite and chlorite are not common and are present in metapelitic or metatuffaceous layers interbedded with the massive sulfide. Calcite-rich sections of the massive sulfide layers lie toward the middle and top in the stratigraphic column of the stratiform sulfide unit and are associated with pyrite and sphalerite more often than pyrrhotite and chalcopyrite. One small exposure rich in tremolite occurs near the stratigraphic top of the Number 5 deposit. Sericite is abundant in the quartz-rich sections of the deposits. Magnetite is present in small amounts throughout the massive sulfide zones, where it commonly appears to have replaced pyrrhotite; it also occurs as isolated crystals in the quartz or chlorite-rich portions of the deposits.

Textures in the massive sulfide bodies are related, in most cases, to deformation. A paragenetic sequence of sulfide mineral formation has been obliterated by the tectonic deformation of the rock mass. The pyrite grains are euhedral and often show granulation; chalcopyrite grains are anhedral and appear to have been plastically deformed around the pyrite grains. Pyrrhotite grains commonly have a weak to well-developed "bird's eye" texture, where alteration to marcasite along

grain boundaries and cleavage planes has produced fine-grained dark rings enclosing unaltered pyrrhotite. Chalcopyrite occurs as isolated grains in quartz gangue or with pyrite, pyrrhotite or sphalerite. Exsolution blebs of sphalerite are often found in the larger grains of chalcopyrite. The chalcopyrite commonly occurs as small grains or blebs associated with pyrrhotite and may represent an exsolution product. In many polished sections examined, the chalcopyrite had deformed plastically, causing it to flow and mold around harder mineral grains; this same process may have produced the high grade (3.3% copper) Number 4 orebody which occupies a fold nose. Quartz grains have recrystallized and fractured in most polished sections examined; sericite, biotite, chlorite and actinolite have all aligned in the dominant foliation direction.

3. Genesis

The stratiform sulfide deposits at the Hidden Creek mine were formed by the precipitation of sulfide minerals from solutions vented onto the sea floor. A well-developed geothermal system circulated seawater into the basaltic volcanic pile and discharged a hydrothermal fluid rich in silica, iron, reduced sulfur and copper. The precipitates formed pyrite, pyrrhotite and chalcopyrite-rich layers interbedded with chert in depressions near the solution discharge sites. An influx of clastic sedimentary debris smothered the mineralizing system and capped the entire volcanic pile. Metamorphism and deformation caused recrystallization, granulation and plastic flowage of the sulfide minerals on small and large scales. Further discussion on genesis of the strataform sulfide deposits is given in Chapter VIII.

## Stratabound Sulfide Deposits

### 1. Form and Internal Features

The Number 2 and 3 deposits at the Hidden Creek mine are composed of massive cupriferous pyrrhotite and pyrite layers and lenses which lie in a highly altered basaltic tuff. These deposits were originally one sulfide zone, but faulting has offset them and for mining purposes they have been considered as two separate orebodies. Most of the Number 2-3 deposit has been removed by mining, leaving only remnants of the orebody in the pit walls and floor. Figure 4 shows the present day configuration of the Number 2-3 deposit, while figure 13 (after Bancroft, 1918, and Nelson, 1935) shows the deposits before mining. The number 2-3 orebody consists of a series of sulfide lenses, layers, and disseminations which lie conformably in an altered basaltic tuff. The lower stratigraphic sections of the deposit grade into sparsely mineralized but highly altered basalt with poor to well-developed stockwork sulfide zones. The upper portion of the deposit grades either into the tabular massive sulfide bodies along the volcanic-sedimentary contact or into altered basaltic tuff.

The sulfide lenses, although large (up to 40 m long and 15 m thick), do not form one tabular body because a significant tuffaceous component was intermittently deposited along with them. The lenticular character may also reflect an irregular primary depositional environment, for example, the presence of depressions or small rifts on top of the submarine volcanic pile. The composite deposit is much larger and the upper, high-grade portion was described by Bancroft (1918) as being 160 m long and 80 m wide. The metabasalt associated with the sulfide

bodies is highly chloritic and contains abundant disseminated sulfide (mainly pyrrhotite) grains. The alteration is premetamorphic and is related to either the passage of hydrothermal fluids or the effect of hot brine pools on the sea floor. Paleo-hydrothermal vents or fumaroles appear as small shear zones, up to 1 m wide, composed of chlorite and actinolite schist. The shears carry small quartz veins, are rich in pyrrhotite and chalcopyrite and cross-cut the underlying pillow lava and tuff at a high angle. Alteration is most intense around the old fumaroles and near the sulfide lenses, and thus provides strong evidence that hot aqueous fluids reacted with the basaltic pile and are intimately linked with the deposition of the sulfide minerals.

The Number 2-3 deposit is conformable with the enclosing rocks and provides a marker horizon for correlation of structural deformation. A well-developed foliation is pervasive throughout the deposit; it strikes 340° and has dips which vary between 40° and 70° west. The deposit is situated on the nose of a northerly plunging, asymmetrical fold that has an overturned east limb. Nelson (1935) refers to the structure of the orebody as being "sprawled over the top of the greenstone spur." The Number 2-3 deposit lies near the fold nose on the west limb and has an average dip of 60° west. The orebody has a rake of 30° to 35° north, which indicates that the original depression in which the sulfides accumulated had a north-south trend.

2. Mineralogy and Textures

The sulfide bodies making up the Number 2-3 deposit are composed of massive pyrrhotite plus variable amounts of chalcopyrite and minor pyrite. Up to 3% copper was present in some ore blocks, but average

mining grades were 2.28% copper from the Number 2 deposit and 1.40% copper from the Number 3 deposit (Nelson, 1935). Sphalerite is present in minor amounts and is associated with the pyritic zones, not the massive pyrrhotite-chalcopyrite bodies. The gangue minerals are pyrrhotite, pyrite, magnetite, quartz, chlorite, actinolite, hornblende, epidote and albite. There is up to 3% magnetite in the massive sulfide zones (Hanson, 1935). Chlorite and actinolite are the main silicate gangue minerals. All minerals are aligned parallel to the foliation and often show deformation on a microscopic scale.

3. Genesis

All available geological data, mine sections, and surface geology indicate that the Number 2-3 deposit represents a massive sulfide horizon which formed on the sea floor during the terminal stages of volcanism. A buildup of basaltic pyroclastic debris, mostly tuff, was cross-cut by a series of fumaroles which fed hydrothermal solutions onto the sea floor. The hot brines collected in overlying depressions, causing alteration of the basaltic tuff and precipitating sulfide minerals. The depositional site may have been a north-south trending depression or slight graben where sulfide deposition occurred near the center and became insignificant near the margins, which would account for the fact that the deposit narrows near the margins and grades into sparsely mineralized basaltic tuff.

## Stockwork Sulfide Deposits

1. Form, Internal Features, and Mineralogy

An epigenetic pattern of mineralized quartz veins and chloritized alteration zones in metavolcanic rocks has been recognized in a number

of massive sulfide deposits around the world and has been termed, "stockwork mineralization". Discussions of such stockwork deposits are numerous and have been given by such authors as Sangster (1972), Hutchinson (1973), and Large (1977), to name but a few. A large area of altered basalt lies west of the Number 2-3 deposit (see figure 4). The alteration in the basaltic rock mass ranges from weak to intense and is composed of three variables: chloritization, silicification and quartz veining, and sulfide enrichment. The alteration either predates or is coeval with the stratiform and stratabound massive sulfide deposits because the overlying argillite sequence shows no hydrothermal alteration effects. Within the large zone of altered basalt a significant enrichment of copper, in the form of chalcopyrite, is widespread (see Chapter VI). Thin, "feathery" quartz and albite veinlets are common, but larger quartz veins several centimeters thick are restricted to several areas in the alteration zone, specifically: west of the Number 2-3 deposit and in the vicinity of diamond drill hole C-13 (see figure 4). The large quartz veins referred to above and the altered basalts near them often carry significant copper mineralization; it is these copper-rich quartz-veined alteration zones that have been termed "stockwork sulfide deposits" at the Hidden Creek mine. The stockwork sulfide deposits have been diamond drilled but have not been outlined as ore bodies because of their low grade and erratic nature; enough data is available from the drill logs to outline the deposits, but such a project is beyond the scope of this thesis.

The stockwork zones cross-cut the metabasalt. Copper mineralization in the form of chalcopyrite occurs as disseminations in the metabasalt and as blebs or masses in the quartz veins. Pyrrhotite and chalcopyrite are the dominant sulfide minerals; pyrite is minor and sphalerite occurs as scattered grains seen microscopically to be associated with the chalcopyrite. Sections of the stockwork deposits contain up to 2% copper, but the overall grades are erratic and are much less than ½% copper; these deposits are geologically significant, but their low grades and tonnages make them uneconomical to mine at the present time.

2. Genesis

The stockwork zones associated with many massive sulfide deposits are commonly considered to be the remnants of channelways for hydrothermal fluids. Spooner and Fyfe (1973) and Large (1977) have described geothermal systems and dealt with their genetic implications in terms of rock alteration and ore formation. The stockwork sulfide deposits at the Hidden Creek mine represent hydrothermal solution channelways that carried copper-rich fluids out of the volcanic pile to be expelled through vents at the seawater-rock interface. The altered basalt represents the composite geothermal system, whereas the stockwork zones represent the main solution channelways which carried saturated hydrothermal fluids.

## METASEDIMENTARY ROCKS

The features and setting of the metasedimentary rocks which overlie the massive sulfide deposits and metavolcanic pile at the Hidden Creek

mine have been discussed in Chapter II. The metasedimentary rocks were originally laid down by a series of turbidity flows which deposited fine clastic sediments composed of quartzo-feldspathic silt and pelite. The beds are commonly 15 cm thick and regularly alternate between siltstone and pelite throughout the stratigraphic column. Metamorphism and deformation have transformed the sedimentary assemblage into what is commonly referred to as "argillite." No marker beds are present in the argillite, making it difficult to correlate specific sedimentary units or geological structures. The metasedimentary rocks all contain a minor amount of carbonaceous material and pyrite, which indicates that deposition took place under reducing conditions. A quiet water basinal environment distal from the source of clastic debris formed the depositional site in which the sediments were laid down.

Alteration of the argillite is in the form of quartz veining and bleaching of fractures near dikes and plugs. The quartz veining is related to structural deformation and not hydrothermal alteration, which accompanied the mineralizing event (it is described in the following section of this chapter). Near intrusive bodies, fractures are surrounded by alteration envelopes that are bleached white and are up to 1 cm, but average several millimeters in thickness. The bleaching is not widespread and is attributed to solutions emanating from nearby intrusive bodies, such as dikes or plugs. The bleaching consists of silicification and sericitization, which is very fine-grained. All of the alteration is post-depositional and, for the most part, is unrelated to the hydrothermal event that generated the massive sulfide deposits.

## QUARTZ VEINING

A broad zone of quartz veining extends nearly 120 m from the massive sulfide deposits out into the surrounding argillite at the Hidden Creek mine. Several small zones are also present near the Number 6 deposit and along the east limb and center of a syncline to the west of the mine (see figure 4). In the area which lies to the east of the Hidden Creek mine, the veining intensity decreases with distance from the quartzite-massive sulfide horizon.

Two sources of silica that formed the quartz veins are the quartzite horizon and the quartz-rich siltstone layers in the metasedimentary rocks. In the quartz-veined zones, outlined in figure 4, both of the above sources contributed to the veins but the quartzite bed was the major silica source. A third and unrelated type of quartz veining, not necessarily spatially associated with either the stratiform sulfide or stockwork zones, is related to younger intrusive rocks.

Near the massive sulfide layers two types of quartz veins occur: one type is significantly deformed while the other is not. The deformed veins are thin and discontinuous with average dimensions 5 mm in width and 30 mm in length. The second type of vein shows little or no deformation and is much thicker and longer than the first type (2 cm to 3 m wide by 5 or more meters in length). Both vein types carry disseminated grains of pyrite, pyrrhotite plus minor chalcopyrite, sphalerite and rarely galena.

Three generations of quartz veins are present. The earliest veining filled tensional fractures associated with the settling of the sediments over the volcanic pile. The first generation of veins is

especially common near the massive sulfide-quartzite beds and may reflect a mobilization of residual fluids in these beds during compaction and settling, caused by the buildup of the overlying sedimentary pile. The early veins have been deformed by later folding and in one locality these highly-deformed quartz veins carry several percent pyrrhotite and chalcopyrite, probably remobilized from the massive sulfide horizon. The second generation veins are the most abundant and were formed during the main deformational event that tilted and folded the volcanic-sedimentary pile. The quartz veins cross-cut each other at 60° and many appear to extend outward normal to the siliceous sulfide beds; these veins formed in conjugate fractures and tensile fractures opened by folding of the argillite and metabasalt. The youngest veins are few in number, continuous, over 1 m wide, and contain pyrrhotite, chalcopyrite, sphalerite, significant galena, plus angular fragments of the surrounding wall rocks. The young veins are believed to be associated with nearby intrusive rocks and are found exclusively in the metasedimentary strata. The quartz veins surrounding the mineral deposits at the Hidden Creek mine are of a tectonic origin and indicate folding near a silica source. The veins have little significance in the interpretation of the mineralizing process for the massive sulfide bodies.

## STRUCTURAL GEOLOGY

The structural geology at the Hidden Creek deposit is dominated by an asymmetrical overturned anticline and a syncline. Figure 4 and cross-sections 4A-A' and 4B-B' show the main structural features. The metabasalt

and argillite lack marker beds, therefore the volcanic-sedimentary contact provides most of the information on folding and faulting in the mine area. The Hidden Creek massive sulfide deposits are located around the nose of a salient of metabasalt that extends into the metasedimentary rocks. The salient is the remnant of an overturned anticline that plunges to the north at approximately 30°. The dip of the volcanic-sedimentary contact is vertical in the southwest corner of the map area (in figure 4); it is overturned from the Number 6 deposit north to about the middle of the 1-5 deposit where it flattens to a steep to moderate easterly dip. The contact on the west side of the salient is shallow and westerly dipping, but steepens on the west side of the syncline shown in figure 4. The axis of the syncline trends northerly and plunges gently in that direction. During mining, it was discovered that the volcanic-sedimentary contact near the ore deposit swings from an easterly dipping to an overturned westerly dipping plane at depth. Additional exploration and drilling by both the Granby Company and Cominco Limited indicated that the contact is folded and dips east to northeast at depth (550 m below the surface). The argillite overlying the metabasaltic pile is deformed into a series of tight folds which range from several meters to several hundred meters in width. Folding in the argillite appears to have no relation to deformation in the adjacent metavolcanic pile, a fact that may be explained by the difference in the competence of the two lithologies. The metabasalt is a massive and generally competent rock mass, unlike the well-bedded and more flexible argillite sequence, therefore strain energy would be released through folding in the argillite and shearing

or faulting in the metabasalt. Due to their close proximity, the massive sulfide deposits deformed in a similar way to metavolcanic strata.

Faults are present in both metasedimentary and metavolcanic strata, but small scale shearing is most common in the metabasalt. The tuffaceous beds and hydrothermally altered basalt formed the least competent volcanic rocks during deformation, and were subjected to the greatest amounts of shearing and foliation. Most faults in the mine area trend in a north-south direction and are vertical to nearly vertical in dip. A major fault is suspected to run along Hidden Creek near the deposits but direct evidence, such as displacement of beds, is lacking. A fault displaced the Number 2 and 3 orebodies, which were originally one unit; they have a steep easterly dip and strike in a north-south direction. Hanson (1935) reported that displacement along this fault was 90 m vertically and 60 m southerly, with the vertical movement dropping the eastern side relative to the western.

## GENESIS AND SUMMARY

The cupriferous massive sulfide deposits at the Hidden Creek mine lie at the volcanic-sedimentary contact or just below it. Three types of deposits have been defined: a stratiform type, a stratabound type, and a stockwork type. The stratiform and stratabound types are lenticular to tabular and are conformable with their host rocks. The stratiform deposits are transitional from volcanic to sedimentary, but show a strong sedimentary character. The stratabound deposits are interbedded with hydrothermally altered basaltic tuff and, during

an explosive phase of volcanism, formed as sediments on the sea floor. The stockwork deposits clearly postdate the volcanic pile, but are directly associated with the hydrothermal alteration of the basalt. All three deposits are related to the same hydrothermal event which began during the terminal stages of volcanism and ended when clastic sedimentation shrouded the area and sealed the geothermal system. The stockwork deposits and alteration zone reflect the area affected by hydrothermal fluids circulating in a geothermal system. The alteration and leaching of the metabasalt produced copper, zinc, iron and silica-rich solutions which were expelled at vents in the sea floor. The saturated solutions precipitated and gave rise to the massive sulfide deposits that form the orebodies at the Hidden Creek mine. Fluid circulation and precipitation of the sulfide minerals continued until clastic sediments encroached upon the recharge-discharge sites for the hydrothermal fluids and sealed them off. Without an adequate fluid supply, the geothermal system could not maintain its fluid output and slowly died out. The area was buried by a thick pile of eugeosynclinal clastic sediment. Intrusion of the Coast Plutonic Complex caused deformation and thermal metamorphism of upper greenschist grades in the Hidden Creek area. Uplift and erosion, mainly in late Tertiary time, have brought the mineralized zones to the surface in their present-day setting.

# CHAPTER IV

## THE DOUBLE ED DEPOSIT

The Double Ed copper deposit is located 4 km west of the former townsite of Anyox (figures 2 and 3). A trail following an old road runs along the southwestern side of Bonanza Creek and terminates at Prison Creek. An overgrown trail connects the road to the surface showing that outcrops in the cliffs forming the southwest valley wall of Bonanza Creek. An adit portal remains open 152 m (500 feet) above sea level near the confluence of Bonanza and Prison Creeks. Helicopter landing sites exist on the waste rock dump near the adit and on a flat plateau above the surface showing. Steep topography and deep gorges make access into the area difficult.

In 1952, Cominco prospectors discovered massive pyrite boulders in the talus and below the Double Ed surface outcrop and traced them to their source. Geological mapping and trenching were conducted in 1952; during 1953 and 1954 a program of detailed geological mapping and diamond drilling was carried out. Most of the drill core, stored in a shack below the surface showing, has been carried away by avalanches. In late 1959 and early 1960 a road was constructed and an adit was driven 762 m to intersect the mineralized strata at an elevation of 152 m. The orebodies were further explored by underground diamond drilling and this drill core is stored near the adit portal. No physical work has been performed on the property since 1960.

In 1976 the writer spent three weeks mapping the surface and underground geology, and examining the remaining drill core. D. W. Heddle had mapped the surface geology in 1953 and 1954, and F. D. Gill mapped the underground geology in 1960. The writer modified the original mapping by subdividing the rock units near and within the mineralized zones and by introducing metamorphic terminology.

## STRATIFIED ROCKS

At the main volcanic-sedimentary contact near the Double Ed deposit, the metabasaltic volcanic pile is overlain by fine-grained quartzo-feldspathic metasedimentary bands intercalated with metapelitic layers. Approximately 150 m below the contact a metamorphosed, metalliferous sediment-tuff assemblage hosts a significant deposit of cupriferous pyrite and pyrrhotite. Figure 14 shows a composite stratigraphic column through the area. The surface geology is shown in figures 5 and 6; figure 5A-A' is a cross-section of the deposit. The underground geology is shown in figure 7.

### Metabasalt

The metavolcanic assemblage which hosts the Double Ed deposit is composed of tholeiitic metabasalt. A small mass of coarse-grained alkaline pillow lava overlies the tholeiitic horizon and forms a late stage eruption. The original basalt has undergone regional thermal and burial metamorphism of upper greenschist grades that are typical to the area. The metavolcanic pile consists of pillowed lava flows, dikes, sills, and sections of tuff, crystal tuff and agglomerate. An alteration event accompanied sulfide deposition and affected the

LEGEND

| | |
|---|---|
| 6 | Argillite (interbedded quartzo-feldspathic siltstone and pelite), calcareous grits |
| 5 | Quartzite (metachert) |
| 4 | Massive Pyrite and Chalcopyrite with Quartz, Sericite, and minor Sphalerite; crudely bedded |
| 3 | Metapelitic Rocks (strongly altered) |
| 2 | Mixed Metapelitic Rocks and Metabasaltic Tuff (strongly altered) |
| | 2A Tuff more abundant than metapelite |
| | 2B Metapelite more abundant than tuff |
| 1 | Metabasalt: |
| | 1A Porphyritic pillowed flows, close-packed |
| | 1B Porphyritic pillowed flows, interpillow space fillings |
| | 1C Tuff, agglomerate, and pillowed flows |
| | 1D Agglomerate |
| | 1E Tuff |
| | 1F Agglomerate, tuff, tectonic breccia, minor pillowed flows |
| | 1G Coarse-grained pillowed flows |

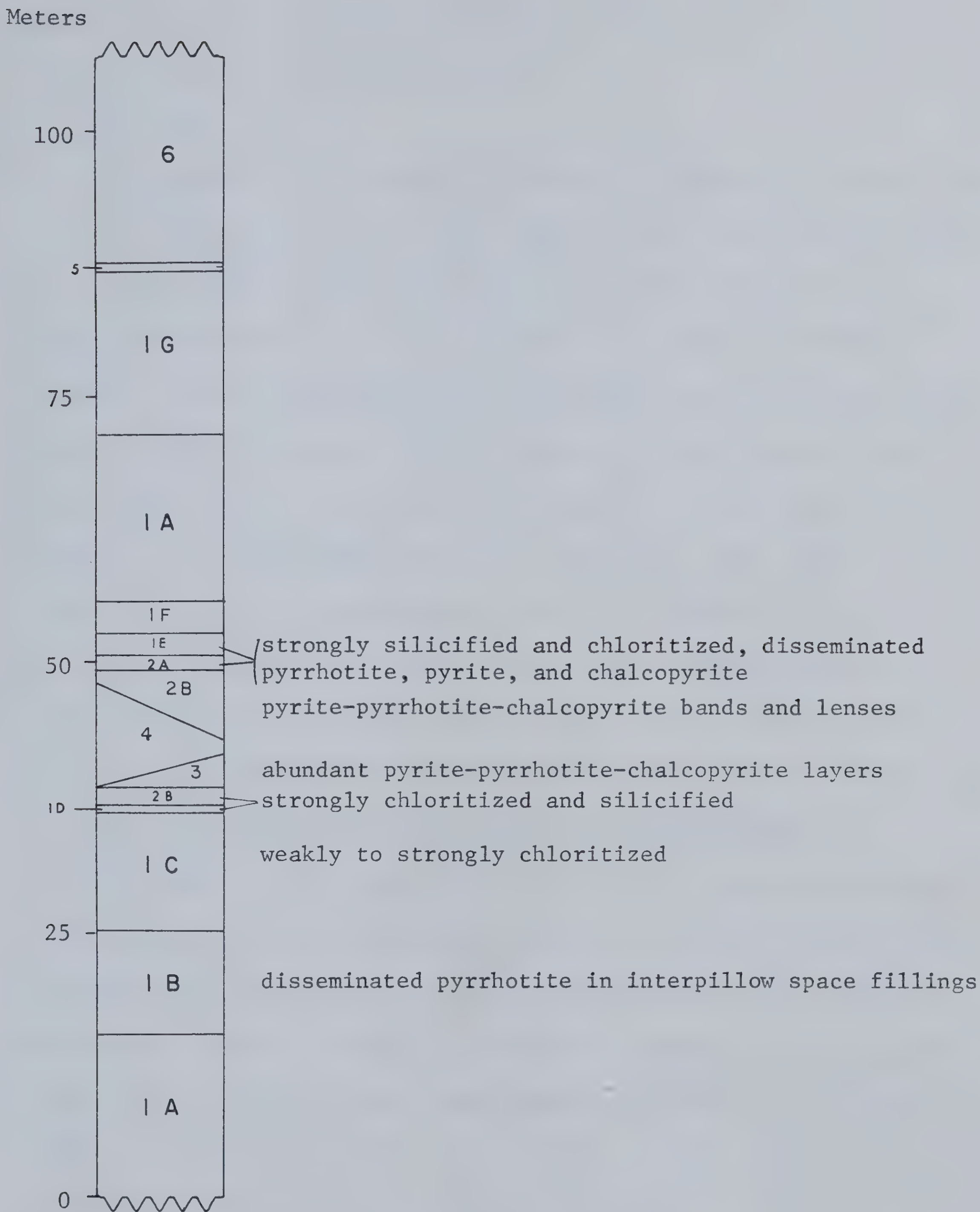



Figure 14. Composite stratigraphic column for the Double Ed area

surrounding rocks, developing distinctive features that are not attributed to regional metamorphism.

1. Lava Flows

The metabasalt is dominantly pillowed, but sections of massive lava occur and are interpreted as either sills or dikes that acted as feeders to overlying vents during active volcanism. The pillows range from several centimeters to over 1 m in diameter and have well-developed selvages. In most outcrops pillows are closely packed and show features resulting from deformation, before cooling, by underlying and overlying flows. Lava tubes are present with the pillows and are often recognizable by the rectangular quartz pod that occupies the center of the tube. Pillow breccia and flow top breccia are present in some outcrops but are not abundant. Pyroclastic layers are associated with most flows, but are generally less than 1 m thick and not laterally extensive. Space fillings between pillows consist of quartz, epidote, calcite, and siderite, with scattered blebs of pyrrhotite and chalcopyrite.

Two types of lava, chemically defined using Irvine and Baragar's (1971) volcanic rock classification scheme, are present near the Double Ed deposit; one is a tholeiitic metabasalt, the other is an alkaline metabasalt. In hand specimen the tholeiitic metabasalt is fine-grained, porphyritic, and contains scattered amygdules, while the alkaline metabasalt is characteristically coarse-grained. In thin section the mineralogy of the two lavas is similar and consists of actinolite and albite which are dominant, followed by sericite, zoisite, chlorite, calcite, and minor hornblende. Magnetite, ilmenite, pyrite, pyrrhotite, and chalcopyrite are present in trace amounts, but form up to 1% of the

rock. Relict pyroxene and plagioclase (labradorite) phenocrysts occur. The plagioclase phenocrysts have been extensively saussuritized and are present as albite, sericite, zoisite, and calcite mineral assemblages. The groundmass has been metamorphosed to an albite, actinolite, chlorite, sericite, and calcite mineral assemblage. The primary flow structure is still visible in most sections, although in some strongly altered flows it is absent.

The massive sulfide deposits are associated with a significant pyroclastic buildup. This pyroclastic accumulation is both underlain and overlain by tholeiitic pillow lava. The alkaline metabasalt overlies the tholeiitic unit to the south and west of the deposit, but thins and disappears to the north; it is unrelated to the sulfide deposit. The presence of pillow lavas above and below the mineralized horizon shows that the sequence formed in a marine setting.

2. Agglomerate

Agglomerates occur locally, but are not extensive. The bombs form subangular masses and lie in tuffaceous horizons. Agglomerate layers are associated with the sulfide deposit. In addition to the pyroclastic textures, there is evidence that a tectonic brecciation, caused by shearing and deformation during folding, occurred in the pyroclastic layer. The large amount of pyroclastic debris indicates a period of explosive volcanism pre- and post-dating the mineralizing event. The most abundant pyroclastic material is tuffaceous.

3. Tuff

Rocks of tuffaceous origin have been recognized at the Double Ed deposit. Crystal tuff and lapilli tuff are present in some beds, but

most tuff has been metamorphosed to a fine-grained, actinolite-chlorite schist. The metatuff has a patchy, banded nature in hand specimen with the layers dominantly composed of actinolite, albite, and chlorite, along with minor to abundant patches of quartz, sericite, zoisite and epidote. The crystal tuff beds have crystals of saussuritized plagioclase, relict pyroxene, and hornblende filled with actinolite and chlorite. Bands of detrital sediment metamorphosed to chlorite-biotite-sericite-quartz schist are intercalated with the metabasaltic tuff layers. The metasedimentary bands become more numerous near the massive sulfide bodies, while the metatuff component sharply decreases in volume.

Sulfide minerals, chiefly pyrrhotite and chalcopyrite, occur as grains and streaks along foliation planes in the chlorite schists. Pyrite is not as plentiful as pyrrhotite in the metatuff and may have broken down to pyrrhotite during the metamorphic event. Small pods of sulfide minerals several centimeters in length and ½ cm thick occur in the lower portions of the mineralized strata, but lenses of massive pyrrhotite-chalcopyrite 5 cm thick and 1 m long are also present. Few portions of the massive sulfide are entirely free from some recognizable tuffaceous component. The massive sulfide zones are both overlain and underlain by metabasaltic tuff, which indicates an explosive period before and after formation of the sulfide layers.

4. Alteration

A premetamorphic hydrothermal alteration, identical to that at the Hidden Creek deposit, is recognizable in portions of the volcanic stratigraphy directly underlying the Double Ed deposit. Chloritization, quartz veining, and sulfide impregnation are present in both outcrop and

drill core. Metatuffaceous rocks show chloritization, which is most intense near the deposit. Pyrite and pyrrhotite, along with minor chalcopyrite, form fine disseminations or blebs along foliation planes and in veinlets. Silicification exists mainly as deformed quartz veinlets and irregular deformed quartz knots; it may be pervasive throughout portions of the rock mass. The geochemistry of the altered rocks is discussed in Chapter VI.

The alteration is most intense in the area between the two sulfide zones that outcrop at the surface (figure 6). North of an east-west trending fault that truncates the sulfide zone is a section of chloritized and silicified tuff and agglomerate. The fault has a right lateral displacement of approximately 150 m, a movement which would bring a portion of the altered lower metavolcanic strata into contact with the mineralized zone. Although altered, the rock mass north of the fault is unmineralized, which indicates that the development of sulfide mineralization was laterally restricted.

Alteration features in the wall rocks of the adit have been obscured by the intrusion of dikes and plugs. In the vicinity of the sulfide-rich horizon, the rocks show moderate to intense chloritization plus silica and sulfide introduction. This alteration is spatially restricted to the vicinity of the sulfide-rich zones and dies out rapidly within a distance of 30 m. The western side of the mineralized zone is the stratigraphic bottom, while the eastern side is the top. Alteration in the rocks underlying the deposit in the adit is similar to that on the surface. The lavas that capped the sulfide horizon underwent little hydrothermal alteration, chiefly the sulfide veining

and the infilling of interpillow interstices with epidote and quartz.

Prochlorite is common in the altered rocks; locally it occupies hornblende or actinolite pseudomorphs, but usually forms masses that parallel the foliation. Actinolite is present in the less altered rocks and is the most abundant mafic mineral in the metabasaltic flows. In the altered pillow lavas, the chlorite-actinolite-albite groundmass has lost its relict flow alignment and the plagioclase phenocrysts have been heavily saussuritized and sericitized. Silicification and sulfide enrichment of the metabasalt is spatially restricted to the vicinity of the stratabound sulfide zones; it occurs mainly as quartz and sulfide veining, but in local areas has extensively permeated the basalt.

### Metasedimentary Rocks

The rocks overlying the metabasaltic pile are composed of metamorphosed quartzo-feldspathic siltstone interbedded with pelitic rocks in an assemblage referred to as "argillite" elsewhere in the Anyox area. Impure carbonaceous limestone and calcareous grit lenses are present, but are minor. The argillite, impure limestone, and calcareous grit have been described in the preceding sections on regional geology and on the Hidden Creek deposit. A quartzite bed 3 m thick occurs at the volcanic-sedimentary contact in the adit; this fine-grained quartzite represents a recrystallized chert. The quartzite bed is biotitic in the upper meter, indicating a slight metapelitic component. The quartzite bed is exposed elsewhere along the volcanic-sedimentary contact on the surface, but is thinner (50 cm maximum thickness) and is

non-existent in many places. Bleached envelopes surrounding fractures and veinlets occur in restricted zones in the argillite well above the position of the metabasalt in the stratigraphic column. Microscopic examination revealed that the bleaching is produced by sericitization of the detrital feldspar grains near the fractures. The sericitization may be related to hydrothermal fluids circulating around dikes and plugs that intrude the nearby strata; such a relationship was observed in outcrop 1 km north of the Bonanza deposit.

## INTRUSIVE ROCKS

Intrusive rocks occur in the form of dikes, sills and plugs. Dikes range from several centimeters to over 9 m in thickness, while the plugs and sills are composed of amphibolite bodies with dimensions that range from 10 to 50 m. The dikes strike easterly or northeasterly, while the amphibolite bodies, which tend to intrude into noses of folds along the volcanic-sedimentary contact, strike northerly. Am amphibolite stock truncates a portion of the mineralized horizon at the 152 m level and is intersected by the adit west of the sulfide zone (see figure 7).

Diorite is the most common rock type in the dikes. Lamprophyre, felsite and syenite porphyry dikes intrude both the metavolcanic and metasedimentary rocks. In many places the dikes occupy fault zones; angular pieces of fragmented host rocks (fault breccia) are incorporated into dikes along their margins and are commonly visible in diamond drill core. Age relations between cross-cutting dikes are obvious in drill core and outcrop, but correlation is difficult because many dikes of similar composition were intruded after periodic episodes of faulting.

Lamprophyre, basalt, syenite, and diorite dikes all cross-cut the mineralized zone and definitely post-date the sulfide bodies.

The amphibolite intrusive rocks look very similar to the metabasalt, but differ in grain size, lack of flow or pillow structures, and mineralogy. Grain size in the amphibolite ranges from fine to coarse; some contacts have chilled margins. The amphibolite mineralogy consists of an equigranular assemblage of hornblende (locally altered to actinolite) and plagioclase (albite) in the interstices between hornblende crystals. A slight foliation is observable in thin section. Dikes of all compositions mentioned previously intrude the amphibolite, but evidence from underground drilling suggests that the amphibolite may post-date a faulted diorite and felsite dike complex. Age relations between the intrusive rocks are complex, but all intrusive rocks are clearly younger than the metavolcanic-metasedimentary assemblages and the sulfide deposits.

## CUPRIFEROUS SULFIDE DEPOSITS

### Characteristics

The Double Ed copper-zinc deposit consists of massive to disseminated cupriferous sulfides enclosed in metabasaltic rocks. The massive sulfide bodies form layers and lenses which are intercalated with altered basaltic and sedimentary rocks. The mineralized strata are conformable with their metavolcanic host rocks, hence form a stratabound and a stratiform deposit. Because the stratiform nature has been obscured by complex structural deformation, the deposit is commonly referred to as stratabound.

The British Columbia Ministry of Energy, Mines and Petroleum Resources, "Minfile" (1979), lists the reserves at the Double Ed deposit as 3,628,800 tonnes of 1.0% copper and 0.6% zinc. Diamond drilling outlined two mineralized zones in the upper portion and one tabular zone in the lower level of the deposit. At the surface exposure the lower mineralized outcrop is referred to as the Number 1 orebody, while the higher outcrop is called the Number 2 orebody (see figure 6). Faulting and folding severely disrupted the mineralized horizon; it has been folded into a steep, plunging, pipe-like mass.

## Stratigraphy

The sulfide deposits have been subdivided into discrete lithologies which are recognizable in outcrop or diamond drill core (see figure 5, 6, and 7). Figure 15 is a composite stratigraphic column of the mineralized zone and has been divided into the basal, mineralized, and upper sections.

1. Basal Section

An accumulation of pillowed and tuffaceous metabasalt stratigraphically underlies the sulfide horizon. Premetamorphic alteration zones within the lower metabasaltic rocks have been described earlier in this chapter. Two meters below the sulfide-rich tuff bed the pillows are much smaller than the average size seen elsewhere (10 cm by 30 cm, compared to 25 cm by 50 cm); in addition, the amount of sulfide-rich interpillow space filling is unusually high. The interpillow material is composed of pyrrhotite, chalcopyrite, epidote, quartz, albite, biotite and chlorite; it fills vacancies between pillows and it also

LEGEND

| | |
|---|---|
| 3 | Massive Cupriferous Sulfide |
| 2 | Mixed Metapelitic Rocks and Metabasaltic Tuff |
| 1 | Metabasalt: |

1A Pillowed flows, fine-grained

1B Tuff, minor pillowed flows

1C Agglomerate and tuff

1D Tuff

1E Tuff, minor tuffite and metapelitic rocks

1F Fragmental rocks: agglomerate and tectonic breccia

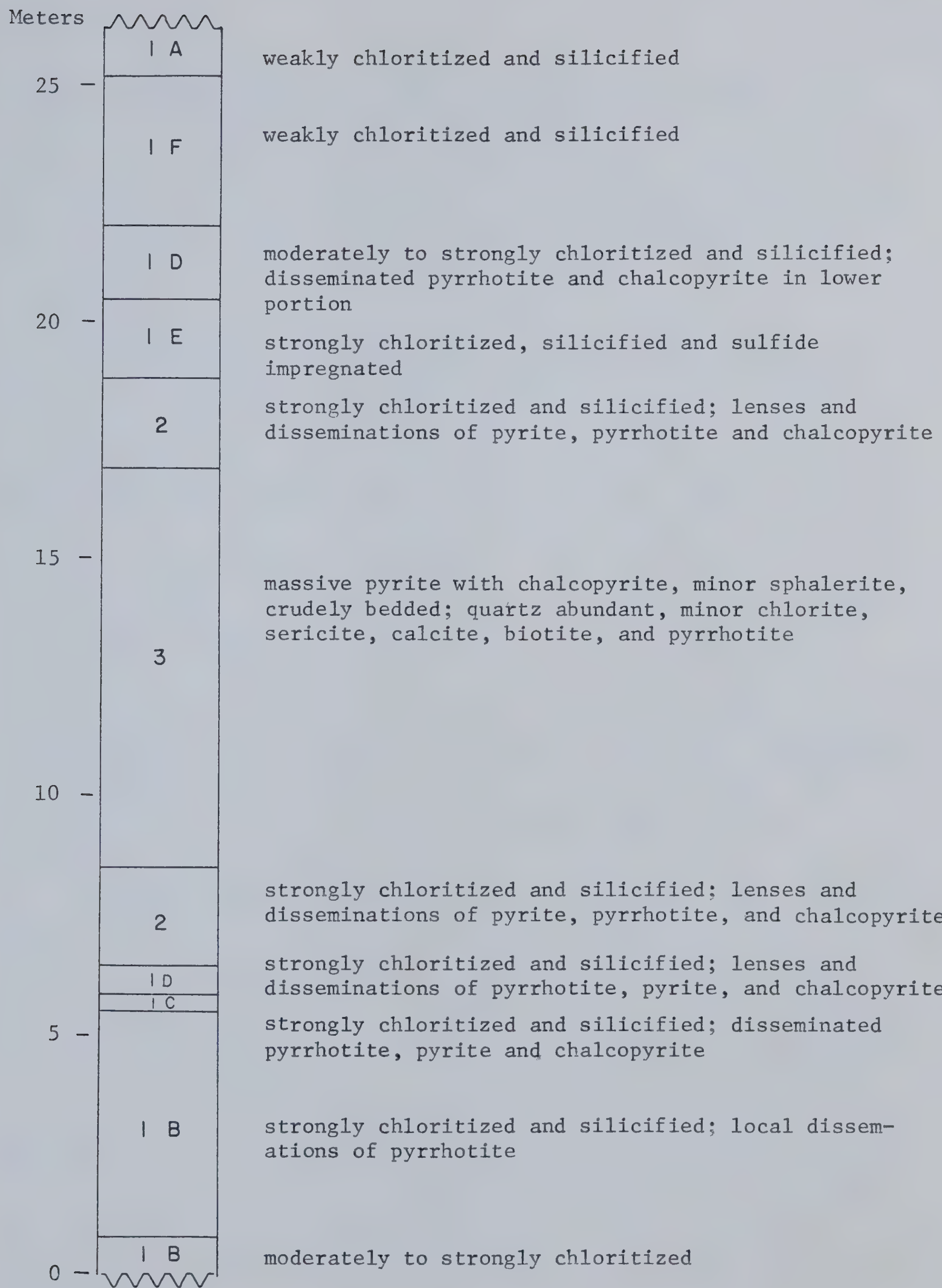



Figure 15. Stratigraphic column for the mineralized zone, Double Ed deposit.

occurs as a matrix material in which the pillows are suspended. Upon extrusion, the pillows probably dropped into a sulfide-rich sediment; any vacancies between pillows were then filled with metalliferous brines and mud carried through the layer by circulating hydrothermal fluids.

2. Mineralized Section

The mineralized strata may be subdivided into three distinct lithologies: tuffaceous, siliceous to pelitic, and massive sulfide. The three lithologies make up a composite zone, enriched in chalcopyrite, where thin, discontinuous layers of each rock type are intercalated with one another. The thickness of the cupriferous zone varies from 10 cm to 30 m. The lithology of the stratigraphic column through the ore zone is composed of hydrothermally altered and sheared mineralized tuffs at the bottom and top, grading into massive sulfide and altered siliceous pelitic rocks in the center. Alteration, metamorphism, and deformation have transformed the tuff into chlorite schist, the pelite into biotite schist, and the chert into quartzite.

The hydrothermally altered basaltic tuff (chlorite schist) contains small quartz bands and veinlets plus disseminated pyrrhotite and chalcopyrite blebs less than 1.2 cm in diameter. Lenses of massive pyrrhotite and chalcopyrite 5 cm thick and 15 cm long lie parallel to the foliation direction. The chlorite schist in this stratigraphic interval is recognizable, in thin section, as a deformed and metamorphosed basaltic crystal tuff and agglomerate. Hydrothermal alteration has extensively chloritized the basalt and saussuritized the original plagioclase crystals within it.

The altered basaltic tuff grades into a dominantly sedimentary layer characterized by hydothermally altered pelitic and siliceous sediment (biotite schist and quartzite). The sulfide lenses in this section are often over 1 m thick and 10 m long and are parallel to the foliation in the enclosing rocks. Pyrite is common and is often the sole sulfide mineral. Chalcopyrite is most abundant in this stratigraphic interval; beds of massive chalcopyrite and quartzite up to 2 m thick and traceable 5 m along strike occur in some of the surface trenches. The gangue mineralogy of the sedimentary section is dominantly quartz and biotite, with subordinate sericite, chlorite, albite, calcite and magnetite. Chalcopyrite and sphalerite are the sole economic sulfide minerals, and pyrite (which is more abundant than pyrrhotite) and pyrrhotite are the gangue sulfides.

The sedimentary section of the deposit contains numerous massive sulfide lenses. The most common lenses are small (5 by 10 cm), composed of pyrite and pyrrhotite in approximately equal amounts with minor chalcopyrite, but locally form up to 60% of the rock mass. Beds of massive chalcopyrite and quartzite, described above, form the high grade sections and tend to occur along the lower contacts of the mineralized layer. The largest and most important massive sulfide accumulations are composed of pyrite, chalcopyrite and quartz lenses up to 9 m wide and 90 m long. The massive sulfide-quartz lenses are identical to those at the Hidden Creek mine but are discontinuous, and while they form a large part of the mineralized outcrop on the surface, they are entirely missing in the adit section.

3. Upper Section

A layer of weakly mineralized tuff and agglomerate overlies, and is gradational into, the mineralized tuff. Tectonic breccia, common in this section, formed when the rock mass was folded into a steeply plunging anticline. Fine-grained to porphyritic pillowed metabasalt overlies the mineralized section, plus the pyroclastic and fragmental rocks. At the base of the pillow lavas, epidote, sulfide, albite, and quartz occur in veins and interpillow space fillings. Sulfide mineralization is minor and extends only several meters into the pillowed lava.

## Sulfide and Gangue Mineralogy

The mineralized zone contains erratic copper and zinc values over an interval up to 30 m thick. The sulfide bodies form thin bands and lenses parallel to the foliation; they rarely form continuous masses except in the siliceous pyrite-chalcopyrite bodies. Copper grades range from 0.1 to 14% copper and from trace to 11% zinc over 1 m intersections. Pyrrhotite and chalcopyrite are the predominant sulfide minerals in the metabasaltic tuff, while pyrite, chalcopyrite, and sphalerite are more common in the pelitic and siliceous metasedimentary rocks.

The paragenetic sequence of sulfide formation from oldest to youngest has been obscured by metamorphism and deformation, but is apparently pyrite, pyrrhotite, chalcopyrite, and sphalerite. Magnetite locally replaces pyrite, pyrrhotite, or chalcopyrite and also occurs as isolated euhedral crystals. Ilmenite crystals occur in the silicate gangue matrix and are rarely in contact with sulfide minerals. It is

possible that the observed paragenetic sequence does not reflect the original formation sequence of the sulfide minerals. Deformation of the rock mass has caused the softer chalcopyrite to flow around and/or invade cracks in grains of harder minerals. Pyrite occurs as euhedral crystals that have been granulated or broken and rotated. Pyrrhotite forms blebs or masses elongated parallel to the foliation; it replaces pyrite and chalcopyrite in some sections. Chalcopyrite-pyrrhotite intergrowths and co-existing minerals are common in most sections except in the siliceous pyritic masses. Pyrrhotite has a characteristic alteration seen in many polished sections where altered rims surround fresh grains or fractures, producing a "bird's eye" texture. The texture reflects the alteration of pyrrhotite to a very fine-grained assemblage of marcasite and magnetite (Uytenbogaardt and Burke, 1971). Sphalerite occurs as scattered grains or occasionally as massive pods several centimeters in thickness; it also appears as tiny exsolution blebs in some chalcopyrite grains.

The non-metallic gangue minerals include quartz, chlorite, biotite, sericite, actinolite, albite, zoisite and muscovite. In the massive sulfide bands quartz, sericite, and biotite are common, along with occasional calcite pods. In the metabasaltic tuff and metapelitic sections chlorite, actinolite, albite, biotite, and quartz are most abundant.

### Genesis

The sulfide deposits are conformable with their host rocks and have been subjected to the same deformational events. These deposits represent both stratiform and stratabound mineralization, but due to

their pipe-like nature are commonly referred to as stratabound. The sulfide deposit formed when a mixture of metalliferous basaltic tuff, siliceous and pelitic sediment accumulated on the sea floor. A pre-metamorphic hydrothermal alteration affected the underlying volcanic rocks and metalliferous sediments during the fumarolic activity that accompanied the break in volcanism. Circulation of seawater into the rock mass and subsequent venting of heated brines on the sea floor resulted in the deposition of cupriferous sulfide in nearby depressions. Renewal of volcanism resulted in the capping of the metalliferous sediments by tuffs and then by pillowed lava flows. Volcanic activity was not entirely absent during sulfide deposition because most of the strata contains some volcanic component, either as pyroclastic fragments or detrital clasts. The rate of accumulation of metalliferous sediment would have had to be rapid (in geological terms), otherwise the continued influx of volcaniclastic debris and tuff would have either diluted the massive sulfide layers or sealed off the hydrothermal system.

## STRUCTURAL GEOLOGY

A lack of distinctive marker beds makes structural interpretation of the area difficult. The volcanic-sedimentary contact is the most distinctive marker, while dikes, lava flow contacts, and mineralized strata provide additional information. The lava flow contacts and sulfide deposits make unreliable marker beds because their original morphology was uneven and subject to erratic changes. Abundant diamond drilling, surface outcrop, and underground access have provided much information on the structure of the mineral deposit. The structure

of the area surrounding the deposit has been defined by surface mapping.

The volcanic-sedimentary contact in the area strikes north-south and has either a steep easterly dip or, where the beds are overturned, a steep westerly dip; southwest of the massive sulfide deposit, diamond drilling has shown that the contact flattens considerably between the surface and the 152 m adit level. South of the surface showings, the contact is warped into an anticline-syncline pair. The anticlinal fold extends to the sulfide deposits and is traced by the contact between the coarse and fine-grained pillow lavas (figure 5, units 6 and 1, respectively). The sulfide-rich strata and the overlying fine-grained pillow lava have been folded into an anticline at the surface.

The sulfide deposits are situated on the east and west limbs of an asymmetrical anticline that has a steep southerly plunge (average $70^{\circ}$). Several faults cross-cut the sulfide zones; a major east-west fault truncates the northern end of the deposits. Diamond drilling has shown that the Number 2 orebody rakes vertically for about 100 m, changes direction and rakes northerly, then is completely faulted off at an elevation of 335 m. The Number 1 orebody rakes vertically for its entire length and forms a tabular sheet 150 to 210 m wide, 12 m thick and over 400 m long (Heddle, 1961). A left lateral fault displaces the southern portion of the orebody at the 152 m level, while the northern portion is folded into a tight anticline (figure 7). A fault and an amphibolite plug truncate the southwest limb of the anticline. The structure of the mineralized strata is complicated because the sulfide bodies developed in a series of troughs or rifts in the

volcanic pile, and had an initially irregular morphology. Correlation of beds after folding and faulting is difficult and complicates any geological reconstruction of the deposit.

Several major faults cut the area. Bonanza Creek occupies a valley formed in part by normal faulting. A left lateral fault displaces the volcanic-sedimentary contact 200 m in the south Prison Creek valley (see figure 3). Near the deposit a right lateral fault which strikes N80°E and dips 65° to 75° N, displaces a feldspar porphyry dike 137 m horizontally (vertical displacement unknown). A second fault striking N50°W and dipping 75° NE intersects the mineralization near the 152 level adit. Dikes have been intruded along fault zones, indicated by the brecciation of the wall rocks at dike margins and the small vertical displacement of stratigraphic units.

## SUMMARY

The Double Ed deposit is a volcanogenic cupriferous sulfide body which is hosted in tholeiitic metabasalt. The conformable nature of the sulfide deposit and host rocks shows that the deposit formed on the sea floor during a break in volcanism. Chalcopyrite and sphalerite are the only economic sulfides associated with pyrrhotite and pyrite gangue. The sulfide minerals precipitated in hydrothermally altered tuffs and pelitic sediments which accumulated in depressions near geothermal vents at the seawater-rock interface. The basalt in the vicinity of the geothermal system reacted with the circulating fluids (mainly heated seawater) and was chloritized, quartz-veined, and imbued with sulfides (mainly pyrrhotite and chalcopyrite). The depressions near

the vent areas were linear and rift-like, probably formed by faulting, and controlled the morphology of the elongated sulfide bodies. A short period of tholeiitic volcanism covered the sulfide-rich strata with basaltic tuff and pillow lava. A small accumulation of alkaline basaltic pillow lava overlies the tholeiitic basalt to the west of the Double Ed deposit, but is not recognized elsewhere in the volcanic pile. The main volcanic-sedimentary break occurs 150 m above the sulfide deposits and is correlative with the Hidden Creek deposits. Regional metamorphism, folding, and faulting have affected the sulfide-rich strata at the Double Ed, mainly by altering the mineralogy of the host basalt and by deforming the sulfide zones.

# CHAPTER V

## THE BONANZA DEPOSIT

The Bonanza deposit is located 2.6 km southwest of the former townsite of Anyox (see figures 2 and 3). Its surface exposure lies 76 m above sea level, 1.28 km northwest of Granby Bay in the Bonanza Creek valley. An overgrown road runs along the southwest side of the valley and connects the old mine workings to tidewater. A helicopter can land on the wasterock dump near the glory hole, but steep topography dominates the area and limits access by foot or air.

Mining operations at the Bonanza deposit were carried out by the Granby Company between 1928 and 1935. Bonanza Creek has cut through the deposit, making it necessary to develop underground entrances on both banks of the creek. The mine workings followed the orebody a distance of 242 m on the northeast side and 600 m on the southwest side of the creek. An aerial tramway conveyed the broken ore from the minesite to the mill at Anyox for concentration and refining. No further work has been done on the deposit since the mine closed in 1935. In 1976 the writer spent ten days mapping the geological setting of the sulfides and the surrounding area.

The Bonanza deposit consists of disseminated to massive layers and lenses of cupriferous pyrite and pyrrhotite, contained in hydrothermally altered basaltic tuff and siliceous pelitic sediments.

The mineralization, host rocks, and geological setting are similar to those at the Double Ed, but the structural deformation has been much less intense. Figure 8 illustrates the surface geology around the Bonanza mine; figures 8A-A' and 8B-B' are cross-sections of the Bonanza deposit. A stratigraphic column of the west limb of the Bonanza anticline is shown in figure 16. All diamond drill core from the deposit was destroyed and exposures of mineralization are limited and disturbed by caving. For these reasons, the geological description of this deposit is brief.

## STRATIFIED ROCKS

### Metabasalt

Metabasaltic volcanic rocks enclose the Bonanza deposit. A series of pillowed and massive flows contains a thick section of pyroclastic rock, which hosts the sulfide mineralization. The pillowed lava flows are all of a tholeiitic basalt composition that has been metamorphosed to an upper greenschist grade. The pillows range from large bulbous masses 2 m in diameter to small rounded structures 10 cm in diameter. In some outcrops the pillow structures have been stretched and flattened by tectonic deformation. The metabasaltic pyroclastic rocks occur in narrow zones throughout the volcanic pile and range from agglomerate to fine-grained tuff. The pyroclastic units are characteristically only a few meters thick, except in the vicinity of the sulfide zone where they are up to 84 m in thickness.

### Sulfide-Rich Strata

The strata associated with the sulfide bodies is composed of metabasaltic pyroclastic and pelitic metasedimentary rocks. These rocks

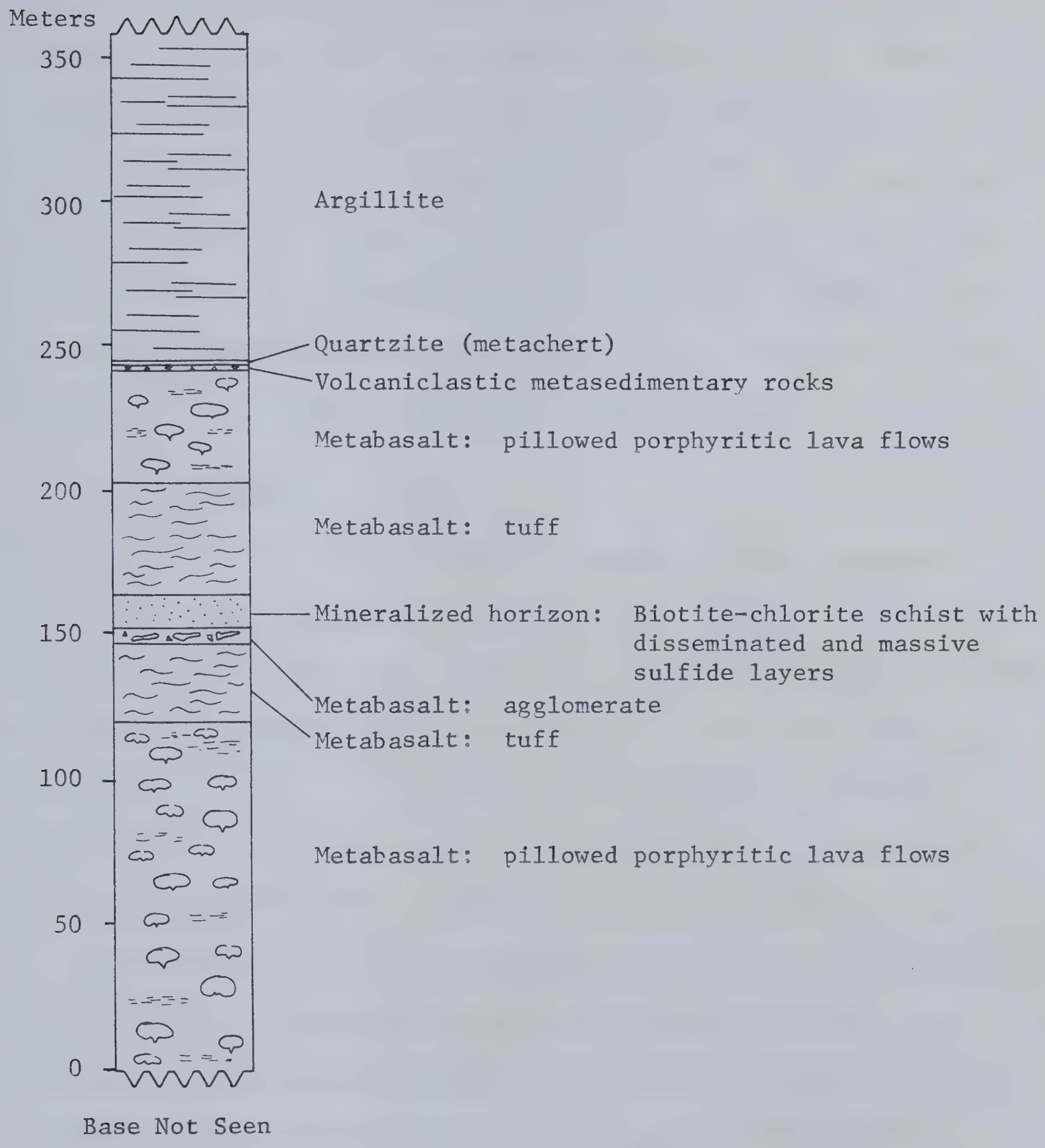



Figure 16. Stratigraphic column of the northwest limb of the Bonanza anticline

underwent a weak to strong hydrothermal alteration prior to regional metamorphism. Chalcopyrite and sphalerite are the economic sulfide minerals which occur with pyrite and pyrrhotite gangue minerals. The average thickness of the mineralized horizon is 22 m. The mineralized strata plunge gently north and have a shallow dip to the west, forming a pipe-like mass that pinches out to the south and is faulted-off to the north; a detailed description of this unit is given later in this chapter under the heading, "Cupriferous Sulfide Deposit".

### Metasedimentary Rocks

The pillowed metabasaltic lavas are capped by thin and discontinuous volcaniclastic rocks up to 1.5 m thick, derived from submarine erosion of the volcanic pile. The unit is gossanous and contains clasts which lie in a chloritic and siliceous matrix; these clasts range in size from 5 to 20 cm. A thin layer of impure quartzite, thought to represent a chert, overlies the volcaniclastic rocks. The quartzite layer, where present, ranges between 2 and 15 cm in thickness.

The majority of the sedimentary rocks exposed west of the Bonanza mine are composed of interbedded quartzo-feldspathic siltstone and shale, which have been metamorphosed to an argillite assemblage typical throughout the map area of figure 3. Fine grains of pyrite and pyrrhotite weather to produce a weak limonitic stain on most outcrops. The siliceous siltstone layers show poorly developed graded bedding. Carbonaceous phyllite to schist (siltstone to shale) is present in the lower part of the argillite unit. For a more complete description of the stratified rocks, see Chapter II.

## INTRUSIVE ROCKS

Numerous dikes are exposed in the Bonanza mine excavations and in outcrops along Bonanza Creek. The most common rock type is diorite, but felsic and thin lamprophyric dikes are also present. A potassium-argon age date of 33 million years was obtained from biotite schist in contact with a diorite dike (Woodcock and Carter, 1976); this date represents a Tertiary age of intrusion of the dike.

## CUPRIFEROUS SULFIDE DEPOSIT

Between 1928 and 1935 the Bonanza deposit produced 724,193 tonnes of ore, grading 2.18% copper. A total of 14,334,358 kg of copper, 105 kg of gold, and 10,653 kg of silver were recovered from the ore (Grove, 1965). The present reserves are 226,800 tonnes of 1.0% copper (British Columbia Ministry of Energy, Mines and Petroleum Resources, "Minfile", 1979).

The Bonanza, like the Double Ed deposit, formed from a siliceous sulfide mud which accumulated in a depression along the flank of a submarine basaltic volcanic pile. A significant build-up of pyroclastic rocks is associated with the deposit. The sulfide minerals are: chalcopyrite, sphalerite, pyrite and pyrrhotite. A chloritic alteration zone is associated with the sulfide mineralization and extends a short distance above (1 m) and below (10 m) the sulfide-rich strata. The Bonanza, unlike the Double Ed or Hidden Creek deposits, has not been strongly deformed but has been tilted, faulted, and has a weak to strong foliation.

Stratigraphy

A generalized stratigraphic column (figure 17) has been constructed from sections measured along the walls of two pits at the old mine workings. Dikes cross-cut the mineralized strata and have been omitted in the column.

The sulfide deposit is underlain by metabasaltic pyroclastic rocks. An agglomerate layer composed of metabasalt bombs up to 35 cm long overlies a thick accumulation of metabasaltic crystal tuff. The bombs lie in a biotite-chlorite schist which represents the metamorphosed equivalent of hydrothermally altered tuff and pelitic sediment. The agglomerate unit is up to 3.5 m thick and contains minor amounts (less than ½%) of pyrrhotite, pyrite and chalcopyrite.

Overlying the agglomerate horizon is a unit that averages 8 m in thickness and was termed the "ore schist" during mining operations. The ore schist layer has been subdivided on the basis of mineralogy and sulfide content; these subdivisions are shown in figure 17. The lower 3 m of the sulfide zone, Unit A, are composed mainly of altered basaltic tuff with a minor amount of altered pelitic sediment, which occurs as a quartz-biotite-actinolite-chlorite schist. The sulfide content of this zone is low, averaging 2% combined pyrite and pyrrhotite with only a trace of chalcopyrite. The overlying 3 m section, Unit B, formed the lowermost ore zone during mining operations; it contains up to 40% pyrrhotite and 10% mixed chalcopyrite, plus pyrite and about 3% magnetite. The biotite-quartz-sericite to chlorite-actinolite ratio is higher in Unit B than in Unit A, which indicates a decrease in the volcanic component and an increase in the sedimentary component of the

LEGEND

| | |
|---|---|
| 4 | Metapelite (strongly altered) |
| 3 | Massive Sulfide |
| | 3A Crudely bedded pyrite, sphalerite, chalcopyrite, and quartz |
| | 3B Bedded pyrite, minor chalcopyrite, quartz, and calcite |
| 2 | Mixed Metapelitic Rocks and Metabasaltic Tuff (strongly altered) |
| | 2A Tuff more abundant than metapelite |
| | 2B Metapelite more abundant than tuff |
| 1 | Metabasalt |
| | 1A Tuff, minor pillowed flows |
| | 1B Agglomerate and tuff (moderate to strongly altered) |
| | 1C Tuff (strongly altered) |

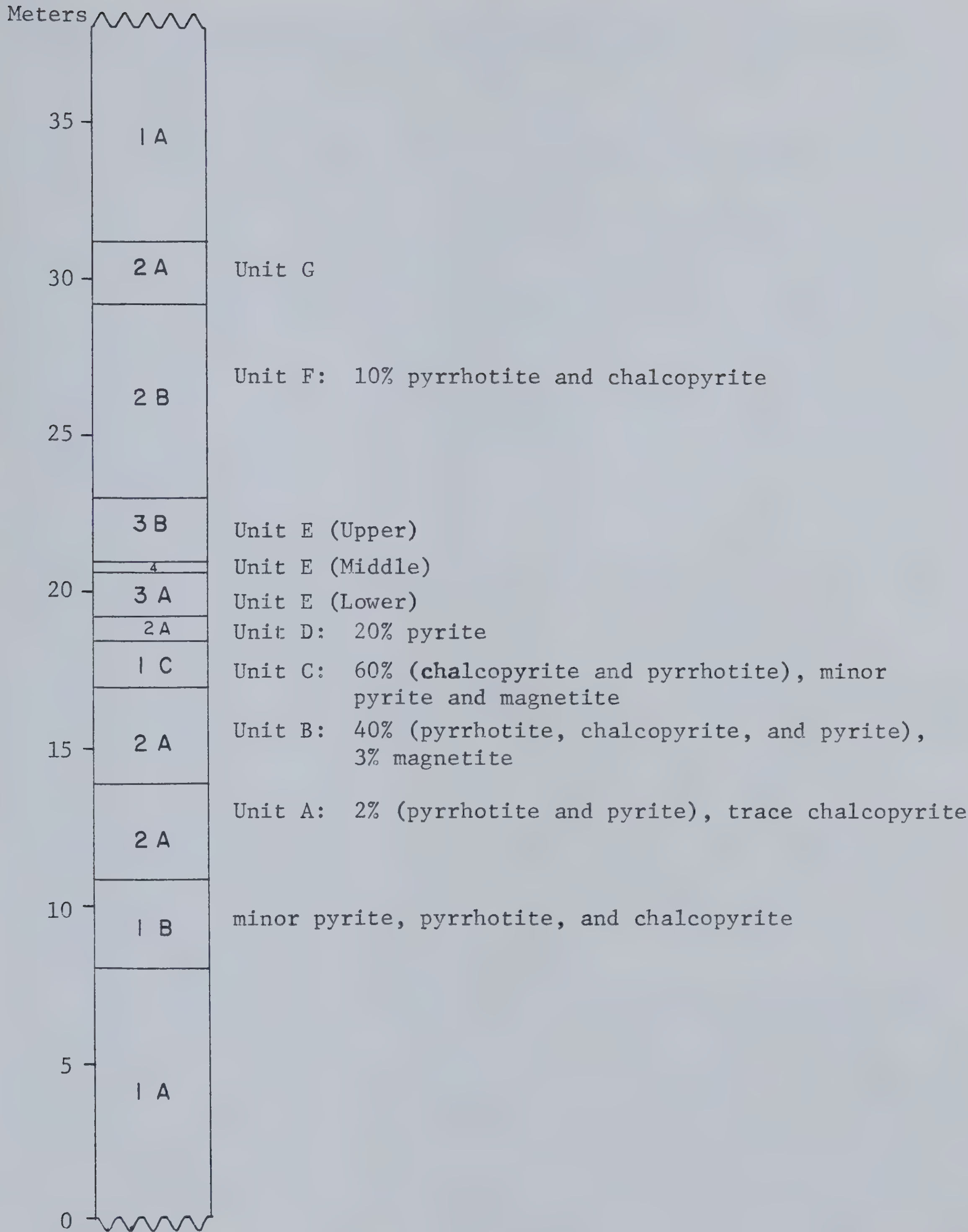



Figure 17. Composite stratigraphic column for the Bonanza deposit

strata. Visual estimates of copper grades in Unit B range between 0.25% and 3%, with averages of 1.5% copper. Unit C is a 1.5 m thick chlorite-actinolite schist which overlies the lower massive sulfide zone and locally contains up to 60% chalcopyrite, 10% pyrrhotite, and minor amounts of pyrite and magnetite. Unit D is a 60 cm thick bed of chlorite-muscovite schist containing 20% pyrite and separating the schistose ore from the bedded massive sulfide ore. The bedded massive sulfide layer, Unit E, is characterized by bands of massive pyrite, chalcopyrite, sphalerite and quartz. The sulfides form disseminated to massive and often crudely laminated layers in a quartz-rich matrix. The lower part of the bedded sulfide zone is made up of a 1.5 m thick layer of bedded pyrite and quartz, with layers containing up to 60% sphalerite over 30 cm thick, as well as up to 5% chalcopyrite associated with the pyrite. An upper bedded pyrite unit up to 2 m thick is present in some sections and consists mostly of pyrite (90%) with traces of chalcopyrite and minor quartz and calcite grains. Where present, the upper section is separated from the lower bedded horizon by a thin muscovite-quartz schist layer 30 cm thick.

The bedded sulfide layers are overlain by Unit F, which is principally a 6.2 m thick chlorite-muscovite-biotite schist containing knots of quartz. Pyrrhotite and chalcopyrite constitute 10% of the rock mass, and chalcopyrite knots up to 10 cm in diameter are scattered throughout this interval. The amount of sulfide minerals decreases toward the top of the layer, but small pods of massive chalcopyrite-sphalerite-pyrite and pyrrhotite occur. The uppermost layer, Unit G, is composed of a quartz-chlorite-biotite schist, 2 m thick, containing scattered pyrite

and pyrrhotite; it grades upward into the overlying metabasaltic crystal tuff horizon.

### Mineralogy

In the Bonanza deposit, the economic sulfide minerals are chalcopyrite and sphalerite, and the gangue sulfide minerals are pyrite and pyrrhotite. Magnetite, titanomagnetite and ilmenite are other metallic gangue minerals. The apparent paragenetic sequence is pyrite, pyrrhotite, chalcopyrite and sphalerite, followed by magnetite in the sections (Units A, B, C and D) below the bedded massive sulfide layer (Unit E). In the massive sulfide unit pyrrhotite is generally absent and the paragenetic sequence is pyrite, sphalerite and chalcopyrite. In the schists (Units F and G) overlying the bedded sulfide zone, the paragenetic sequence appears to be pyrite, pyrrhotite, chalcopyrite, sphalerite, followed by magnetite. In all sections the paragenetic sequence obtained from textures in polished sections is only apparent because deformation has recrystallized and remobilized the sulfide minerals. Magnetite is metamorphic and replaces some sulfide minerals (mainly pyrite).

The silicate gangue minerals are quartz, biotite, chlorite, sericite, muscovite, actinolite, tremolite, albite and hornblende. Calcite occurs as patches and bands in the bedded massive sulfide sections. The grain size of the micas varies from fine to coarse, with some grains up to 1 cm in diameter. Biotite and chlorite are common through the ore zone, except in the massive sulfide layers. Actinolite and albite are most abundant above and below the mineralized section, but also form bands within the ore body.

### Premetamorphic Alteration

Intensive hydrothermal alteration accompanied formation of the sulfide layer at the Bonanza deposit. The alteration effects were restricted to the depositional area and do not appear to have extended very far above or below the sulfide zone. Chloritization extends roughly 1 m above and 10 m below the deposit. Quartz veining and sulfide enrichment is restricted to several meters beneath the sulfide layer. Sulfide deposition occurred in a linear trough filled with basaltic tuff and volcaniclastic debris interlayered with pelitic rocks and chert. The strong chloritization, sericitization, and saussuritization of the mineralized strata indicates that a period of intensive hydrothermal alteration accompanied sulfide formation. Hot, dense metalliferous brines vented into a trough-like depression on the sea floor, similar to that of the Atlantis II Deep of the Red Sea (Degens and Ross, 1969), would produce such alteration of any sediment deposited in the trough. The hydrothermal alteration was restricted to the vicinity of the trough, away from any geothermal vents, because a high thermal gradient between the hot brine and the cold sea floor would limit the alteration effects. The alteration associated with the mineralized zone is premetamorphic because similar alteration is lacking in other rocks nearby, which have undergone the same regional metamorphic event.

## STRUCTURAL GEOLOGY

Two main structural features dominate the area: one is a broad anticlinal fold in the metavolcanic rocks southeast of the Bonanza deposit, and the second is a normal fault that strikes northwesterly

and runs along the Bonanza Creek valley. The Bonanza deposit lies along the west limb of the anticline and has been truncated by the normal fault which also cuts off the north end of the anticline. The anticline has a shallow northerly plunge of about $10^\circ$ to $20^\circ$. The normal fault dips $50^\circ$ NE and has down-dropped the volcanic-sedimentary contact at least 400 m along the fault plane, resulting in a minimum displacement of 303 m vertically and 255 m horizontally.

The foliation of the mineralized strata strikes N39°E and dips $25^\circ$ NW. The footwall of the ore zone in the mine workings, which may represent original bedding, strikes N25°W (Nelson, 1936). The overall form of the deposit is one of a flattened cylindrical body with tapering ends that rakes northeasterly at $10^\circ$. The footwall of the orebody was described as having numerous "rolls and flats" (Nelson, 1936), which would result from an originally irregular depositional surface rather than structural deformation.

## SUMMARY

The Bonanza massive sulfide deposit is a moderately deformed cupriferous pyrite-pyrrhotite body that is conformable with a series of metabasaltic pillow lavas and tuffs. A significant pyroclastic buildup, which ranges from finely bedded crystal tuff to coarse agglomerate, accompanied the mineralization. Hydrothermal alteration of the volcanic rocks accompanied sulfide deposition in a trough-like depression. The mineralized strata passes from barren to weakly mineralized tuff in the basal section, into a massive pyrite in the center, then grades to weakly mineralized and finally barren tuff at

the stratigraphic top of the deposit. The sulfide mineralogy is simple, with chalcopyrite and sphalerite as the copper and zinc-bearing minerals, while pyrite and pyrrhotite form the sulfide gangue. Like the Double Ed, the Bonanza is a volcanogenic stratabound deposit; both are similar to the Hidden Creek deposits in terms of mineralogy, alteration and genesis.

## CHAPTER VI

## GEOCHEMISTRY

The major and trace element geochemical variations of the rock mass hosting the cupriferous sulfide deposits at Anyox provide important data on original, magma types, tectonic setting of volcanism, hydrothermal alteration, and trace element enrichment and dispersion. Magma type and the tectonic setting of the volcanism are important factors in the development of a genetic model of the mineralizing process that produced the Anyox deposits. Hydrothermal alteration is associated with many volcanogenic massive sulfide deposits (Sangster, 1972; Spooner and Fyfe, 1973; Graf, 1977; Large, 1977) and played an important role in the genesis of the Anyox deposits. Trace element contents of the bedrock and the dispersion of elements along the volcanic-sedimentary contact are useful in predicting the presence of massive sulfide bodies nearby.

An extensive suite of rock samples was analyzed for major and trace elements by Cominco Limited as part of their geological exploration of the Anyox area, and by the writer as part of this thesis research. The chemical data incorporated in this chapter was obtained from rock samples gathered during field study in 1976. Analytical results, according to sample sites, are given either in the tables in Appendix I or are displayed in figures 5, 7, and 8. All sample locations are shown in figures 4, 5, 6, 7 and 8. Sampling procedure and analytical methods are given in Appendices II and III, respectively.

## CHEMICAL CLASSIFICATION OF ROCK TYPE

The massive sulfide deposits at Anyox are intimately associated with metabasaltic volcanic rocks. The Bonanza and Double Ed deposits are completely enclosed in metavolcanic rocks, while the Hidden Creek deposit straddles the volcanic-sedimentary contact. Because the magma type may be an important factor in the genesis of the copper sulfide bodies, a suite of metavolcanic rocks unaffected by premetamorphic hydrothermal alteration was analyzed to determine the major element concentrations. The chemical classification scheme developed by Irvine and Baragar (1971) was selected by the writer because it applies to fresh as well as metamorphosed volcanic rocks. Chemical analyses of rocks that were subjected to premetamorphic hydrothermal alteration were not used in this classification scheme. Table 2 lists the rock samples in the Anyox area according to chemical classification. The majority of the rocks fall into the sub-alkaline division, but some alkaline rocks are present. The alkaline lavas form a small mass of coarse-grained pillowed flows southwest of the Double Ed deposit (figure 5, unit 6). The alkali metabasaltic lavas are classified as part of the sodic series, and may represent either spilitized basalts or the original magma composition. The majority of the rocks grouped in the sub-alkaline class are tholeiitic metabasalt. The tholeiites have been subdivided into average, potassium-rich, and potassium-poor series. Rocks at the Double Ed are either of the average or potassium-poor series, while those at the Hidden Creek are mixtures of all three series. Lack of potassium-rich tholeiitic metabasalt at the Double Ed

Table 2. Chemical Composition of the Metavolcanic Rocks at Anyox, B.C.

THOLEIITIC METABASALT, AVERAGE SERIES

| | |
|---|---|
| HC- 17 (Hidden Creek) | 0-279 (Hidden Creek) |
| 0-274 (Hidden Creek) | S-515 (Double Ed) |
| 0-278 (Hidden Creek) | S-578 (Double Ed) |

THOLEIITIC METABASALT, POTASSIUM-POOR SERIES

| | |
|---|---|
| HC- 43 (Hidden Creek) | S-537 (Double Ed) |
| 0-275 (Hidden Creek) | S-540 (Double Ed) |
| 0-276 (Hidden Creek) | S-565 (Double Ed) |

THOLEIITIC METABASALT, POTASSIUM-RICH SERIES

HC- 44 (Hidden Creek)
HC- 45 (Hidden Creek)

CALC-ALKALINE (HIGH ALUMINA) METABASALT

POTASSIUM-RICH SERIES

HC- 18 (Hidden Creek)

AVERAGE SERIES

U4-202.5 (Double Ed)

ALKALI METABASALT, SODIC SERIES

S-579 (Double Ed)
S-580 (Double Ed)
A- 14 (Double Ed)

deposit may reflect a lower sample density at this deposit than at the Hidden Creek deposit. Two samples of calc-alkaline (high alumina) metabasalt were discovered; one is of the potassium-rich series from the Hidden Creek deposit and the other is of the average series from the Double Ed deposit. These two samples appear to be unaltered lava flows; in hand specimen and outcrop they seem identical to the tholeiitic lavas elsewhere, but are chemically distinguished by their high alumina content. Contamination by inclusion of feldspathic sedimentary material is possible, but it is more likely that the analyses reflect the chemistry of the original lava flows.

The massive sulfide deposits at Anyox are associated with metamorphosed tholeiitic basalt. No chemical analyses of unaltered rocks associated with the Bonanza deposit are available, but the lavas are microscopically and megascopically similar to the tholeiitic metabasalt found elsewhere in the metavolcanic pile at Anyox. The association between copper deposits and basaltic rocks has been recognized on a worldwide scale: Troodos, Cyprus; Besshi, Japan; and Løkken, Norway are examples. The relationship between the Anyox massive sulfide deposits and their metavolcanic host rocks is further discussed in Chapter VIII.

## TRACE ELEMENTS AND TECTONIC SETTING OF ORE DEPOSITION

The extensive accumulation of pillowed lava flows which are overlain by fine-grained clastic sedimentary rocks indicates that the formational environment of the massive sulfide bodies was submarine. The tectonic setting of the volcanism and sulfide formation at Anyox

may have been island arc, ocean floor or ocean island. Because Anyox forms a roof pendant in the Coast Plutonic complex and because a number of major faults disrupt the regional continuity of rock formations, a method independent of correlation between regional stratigraphic assemblages is needed to define the tectonic setting during sulfide deposition. Pearce and Gale (1977) have developed a method of identifying tectonic environments associated with massive sulfide deposits, based upon selected trace element geochemistry of the host igneous rocks. This classification system uses elements that are relatively immobile during metamorphism and weathering because most massive sulfide deposits occur in metamorphosed rocks. The stable trace elements used in the present study are titanium (Ti), zirconium (Zr), yttrium (Y), and chromium (Cr), all of which are known to exhibit systematic differences between basalts extruded in different tectonic settings (Pearce and Cann, 1973; Pearce and Gale, 1977). Table 3 lists the mean concentrations (in parts per million) of trace elements present in the three main oceanic magma types, plus those in the Anyox metabasalt. The Anyox tholeiitic metabasalt is most similar to the ocean floor tholeiitic basalt in all but the rubidium (Rb) and barium (Ba) content, which shows similarities to ocean island basalt.

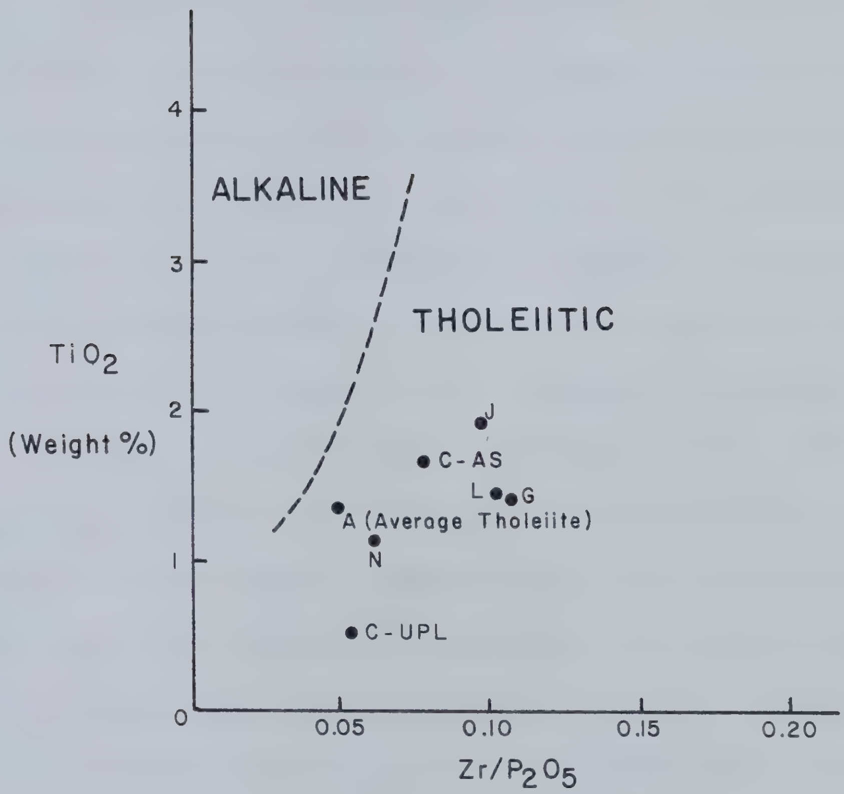
Trace elements that are stable during metamorphism may also be used to distinguish alkaline and tholeiitic basalt. Floyd and Winchester (1975) have developed a plot of $TiO_2$ versus $Zr/P_2O_5$ to divide the two types of basalt. Figure 18 shows the plot with the position of the Anyox metabasalt falling inside the tholeiite field. This plot, utilizing trace elements, is additional support for

Table 3. Mean Concentrations of Trace Elements*
(parts per million)

| | Ocean Floor Tholeiites | Island Arc Tholeiites | Ocean Island Basalt | Anyox Tholeiites** |
|---|---|---|---|---|
| Ti | 8400 | 5000 | 13,500 | 8020 |
| Zr | 83 | 45 | 211 | 78 |
| Y | 28 | 18 | 27 | 33 |
| Nb | 2.5 | 1.5 | 27 | 5 |
| Cr | 280 | 107 | 200 | 218 |
| K | 1300 | 2700 | 5450 | 1894 |
| Rb | 2.5 | 4.7 | 13 | 9 |
| Ba | 8.5 | 60 | 176 | 150 |
| Sr | 120 | 175 | 415 | 159 |
| Cu | 73 | 62 | 81 | 69 |

* After Pearce and Gale, 1977.

** Writer's and Cominco's Research Data




C-AS Cyprus - Troodoos Massif - Axis Sequence

C-UPL Cyprus - Troodoos Massif - Upper Pillow Lava

L Løkken, Norway

J Joma, Norway

G Gjersvik, Norway

N Noranda, Ontario

A Anyox, British Columbia

Figure 18. Magma type and tectonic setting discrimination using immobile elements (after Floyd and Winchester, 1975; Pearce and Gale, 1977).

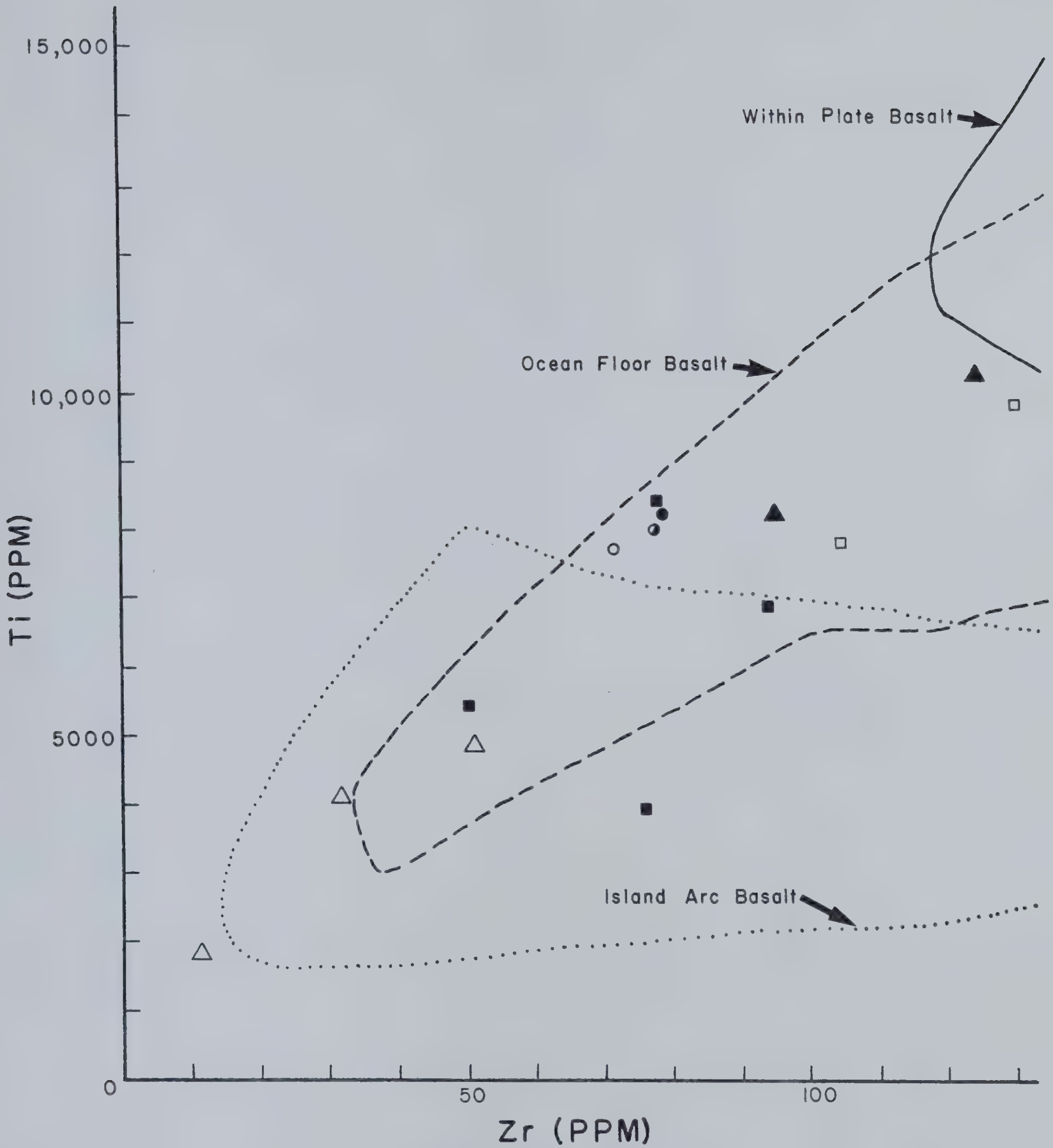
classifying the metabasaltic rocks at Anyox as tholeiitic. Similar deposits have been plotted and fall into the tholeiitic field as well.

Table 4 lists the mean concentrations of stable trace elements of the associated metabasaltic rocks for six massive sulfide deposits; these figures are derived from Pearce and Gale (1977), and from the writer's analyses. The data in Table 4 is plotted in figures 18, 19, 20, and 21, which are discrimination diagrams used by Pearce and Gale to identify tectonic environments of lava extrusion. The fields of different magma types, outlined in figure 19, indicate a progressive increase of titanium and zirconium in basaltic lavas erupted in island arc, ocean floor and within-plate tectonic settings. In figure 19, the Anyox magma type plots within the ocean floor basalt field, indicating that the lavas were extruded onto the floor of an ocean basin and not an island arc or oceanic island. Figure 20 is a plot of the zircon: yttrium ratio versus the titanium:yttrium ratio and is meant to distinguish within-plate basalt from basalt extruded at plate margins; this figure indicates that the Anyox lava was extruded near a plate margin. Figure 21 is a plot of titanium against chromium and is used to subdivide the plate margin basalt of figure 20 into "ocean floor" or "island arc" basalt. In figure 21, the Anyox metabasalt is shown to have erupted on the ocean floor and not on an island arc. Thus, figures 18, 19, 20, and 21 all indicate that the metabasaltic lava at Anyox is tholeiitic and was extruded onto the ocean floor near a plate margin.

The trace element data in Table 4 and the corresponding discrimination diagrams indicate that the magma types and tectonic setting of

Table 4. Mean Concentrations (PPM) of Stable Elements in Metabasaltic Host Rocks for Six Massive Sulfide Deposits.

| DEPOSIT | LOCATION OF LAVAS | Ti | Zr | Y | Nb | Cr | $P_2O_5$ (wt. %) | No. of Analyses |
|---|---|---|---|---|---|---|---|---|
| 1 Cyprus Deposit | Troodos Massif (Axis Sequence) | 5900 | 61 | 28 | 1 | 100 | 0.08 | 85 |
| | Troodos Massif (Upper Pillow Lavas) | 3270 | 31 | 15 | 1 | 405 | 0.06 | 45 |
| 2 Løkken, Norway | Løkken | 8550 | 93 | 26 | 4 | 221 | 0.09 | 38 |
| 3 Joma, Norway | Joma | 11400 | 171 | 26 | 35 | 367 | 0.19 | 5 |
| 4 Gjersvik, Norway | Gjersvik | 8400 | 73 | 27 | 5 | 24 | 0.07 | 16 |
| 5 Noranda, Ontario | Noranda | 7150 | 92 | - | - | 157 | 0.13 | 78 |
| 6 Anyox, British Columbia | Double Ed Deposit | 8020 | 78 | 33 | 5 | 218 | 0.16 | 9 |




△ Cyprus Type

▲ Løkken Type

□ Joma Type

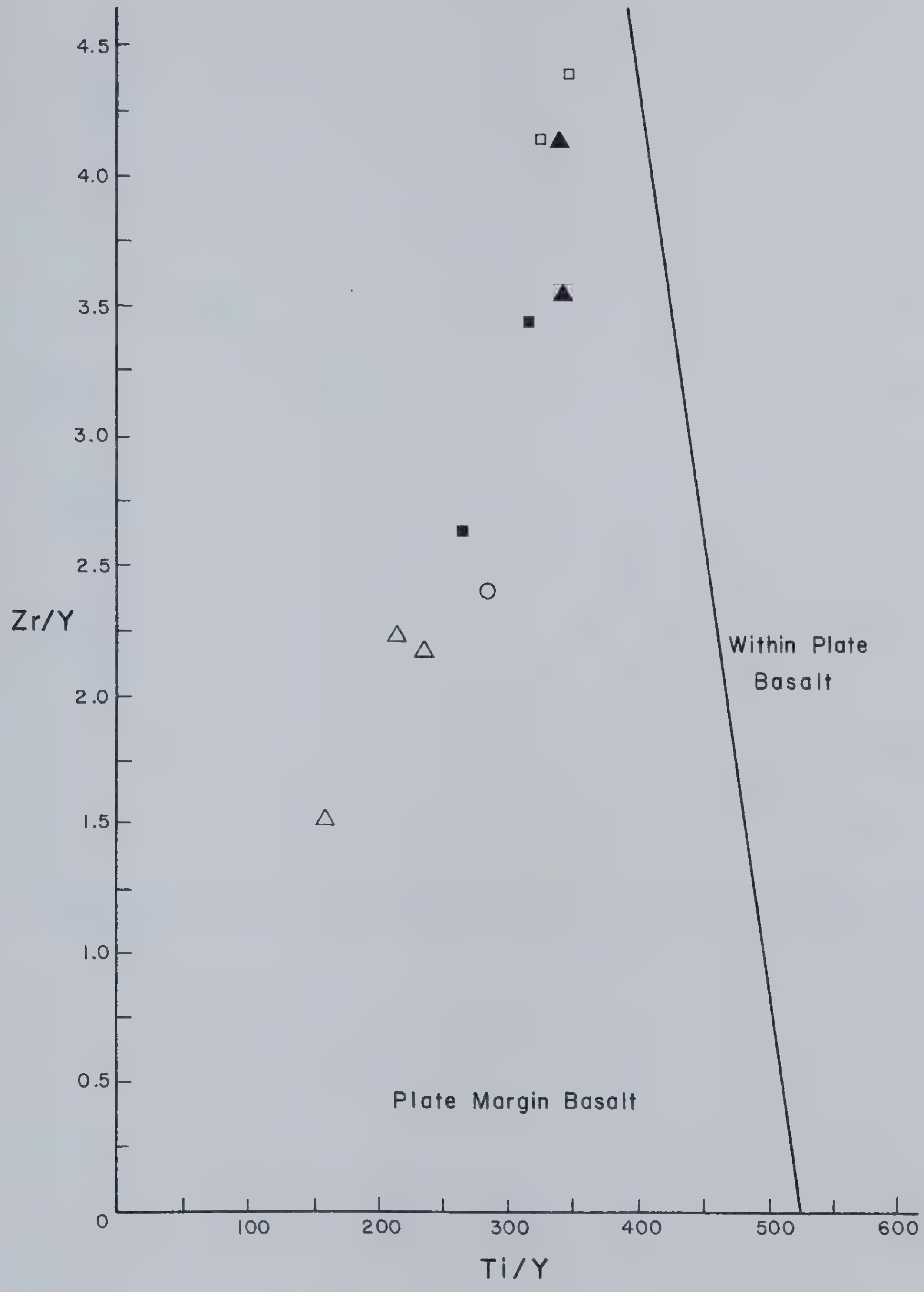
■ Gjersvik Type

● Anyox Type - Mean Tholeiitic

◐ Anyox Type - Mean Alkaline

○ Anyox Type - Mean Alkaline and Tholeiitic

Figure 19. Mean analyses from Anyox and other massive sulfide deposits plotted on Ti-Zr discrimination diagram (after Pearce and Gale, 1977).




△ Cyprus Type
▲ Løkken Type
□ Joma Type
■ Gjersvik Type
○ Anyox Type (Tholeiitic)

Figure 20. Mean analyses of metabasalt from Anyox and other massive sulfide deposit types plotted on Zr/Y - Ti/Y discrimination diagram (after Pearce and Gale, 1977).

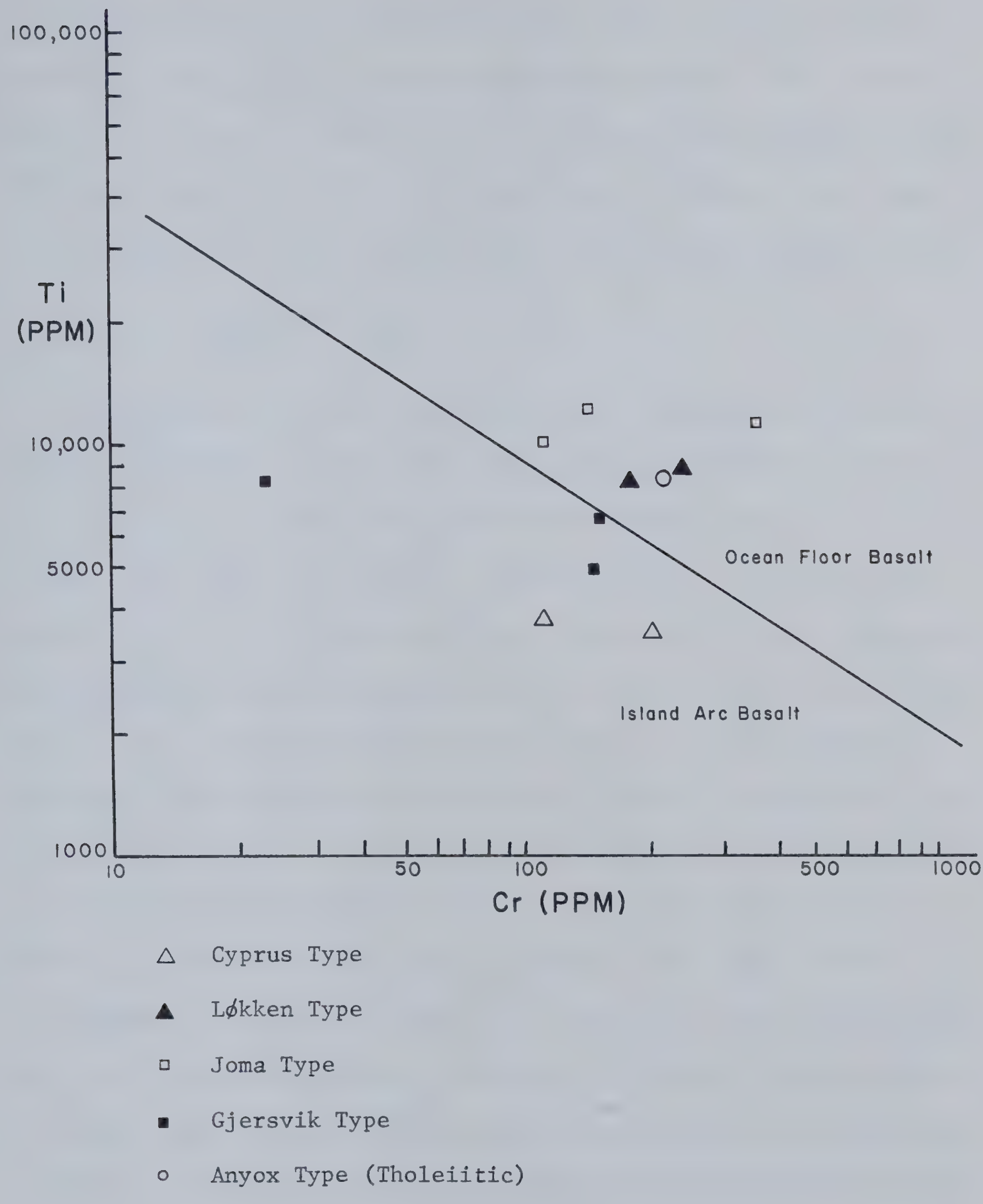



Figure 21. Mean analyses of metabasalt from Anyox and other massive sulfide deposits, plotted on log Ti - log Cr discrimination diagram (after Pearce and Gale, 1977).

eruption are similar for Anyox and Løkken. In both deposits copper is greater than zinc and both have associated gabbroic but no ultramafic rocks exposed. Pearce and Gale (1977) and Vokes and Gale (1976) favor a back-arc setting for the Løkken lavas, similar to that found in the present day Marianas basin which underlies the Philippine sea.

## ROCK ALTERATION

The effects of sea floor rock alteration associated with active geothermal systems have been well-documented by a number of authors, such as Spooner and Fyfe (1973), Hutchinson (1973), Bonatti et. al. (1976), Graf (1977), Large (1977), and Rona (1978). Wallrock alteration occurs when hydrothermal solutions circulate through a rock mass; many volcanogenic massive sulfide deposits overlie distinct alteration zones. In all three deposits studied at Anyox, a recognizable premetamorphic hydrothermal alteration of the rock mass is present. The zone of altered rock is most extensive at the Hidden Creek deposit and is present on a more restricted scale at the Double Ed and Bonanza deposits. The altered rocks contain chlorite, thin quartz veins, and are impregnated by sulfide grains. Microscopically, the altered basalt has minor to abundant chlorite, actinolite, pyrite, pyrrhotite, chalcopyrite and magnetite, extensively saussuritized plagioclase phenocrysts or grains, plus tiny quartz-albite veinlets which cut the thin sections. Unaltered rocks contain less chlorite or sulfide minerals and are not veined by quartz. Both altered and unaltered rocks have been metamorphosed to the upper greenschist facies by regional thermal metamorphism. Field aspects of the rock alteration associated with each deposit have

already been discussed in the preceding chapters.

## Chemical Gains and Losses in Altered Rocks

In active hydrothermal systems it has commonly been found that a chemical reaction between the wall rocks and the circulating aqueous fluids occurs, effecting an exchange of element between the fluids and the rock mass (Kajiwara, 1973; Large, 1977). The exchange of elements occurs as gains or losses of cations attached to the oxygen anions, which compose the bulk of the host rock silicate minerals. Barth (1948) points out that most rock alteration proceeds with little change in volume between altered and unaltered rocks, because the exchange is principally cations and not oxygen. Barth developed the concept of a "standard cell" which is a measure of the number of cations associated with 160 oxygen anions in the rock sample. A gain or loss of cations resulting from alteration is apparent when altered and unaltered rocks of similar original composition are compared. The calculation of the number of cations associated with the 160 oxygen ions in the standard cell is based upon the original chemical analysis of the rock. A sample calculation is given in Appendix IV-a.

The standard cell concept was used by Osatenko (1977) in a similar investigation of the rocks at the Hidden Creek deposit. The present study uses Osatenko's unpublished data plus additional chemical analyses obtained by the writer during his research. A suite of altered rock samples collected from the Hidden Creek and Double Ed deposits was analyzed to determine the major element concentrations present. Results of the chemical analyses are listed in Appendix IV-b, where they have been divided into separate groups depending upon their field

setting, alteration mineralogy and intensity. The chemical analyses of each group were averaged and the averages corrected to 100 weight percent, then the number of cations in the standard cell were calculated and are listed in Table 5. Gains and losses of cations from the altered rocks, with reference to the standard cell of the unaltered rocks, are listed in Table 6. The data in Table 6 shows that different types of alteration have produced a different pattern of cation gain and loss from the altered rocks.

The metabasaltic pillowed lava flows are classified into four groups: unaltered, weakly altered, strongly altered and weakly albitized. Table 6 shows that aluminum, calcium and phosphorous are all lost from the altered lava, while titanium and ferric iron are gained. The most significant loss is that of calcium, especially in the strongly altered rocks. The weakly altered rocks show significant losses of calcium and aluminum, along with an important gain of silica. Minor gains of iron, magnesium, and titanium occurred along with minor losses of sodium, potassium and phosphorous. The strongly altered rocks are heavily depleted in calcium and moderately depleted in sodium and silicon. Significant gains of iron and magnesium, minor gains of potassium and titanium, and minor losses of aluminum and phosphorous are present in the strongly altered rocks. The weakly albitized rocks show a significant gain of sodium and silicon, along with a significant loss of ferrous iron and magnesium. A minor loss of aluminum and gain of ferric iron and titanium are also apparent.

Mineralogical changes that may explain the chemical trends have been observed in thin sections made from altered rocks in the deposits.

Table 5. Cations in Standard Cell

| OXIDE | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $SiO_2$ | 46.9 | 48.9 | 44.3 | 49.2 |
| $Al_2O_3$ | 17.0 | 15.0 | 15.3 | 16.9 |
| $Fe_2O_3$ | 0.7 | 1.2 | 2.7 | 1.4 |
| FeO | 7.4 | 7.7 | 9.8 | 6.1 |
| MgO | 11.6 | 11.9 | 13.4 | 9.0 |
| CaO | 12.0 | 7.9 | 3.2 | 7.7 |
| $Na_2O$ | 4.5 | 4.4 | 2.2 | 7.0 |
| $K_2O$ | 0.3 | 0.2 | 0.4 | 0.3 |
| $TiO_2$ | 1.0 | 1.2 | 1.1 | 1.1 |
| $P_2O_5$ | 0.2 | 0.1 | 0.1 | 0.2 |
| $(OH)^-$ | (7.9) | (10.8) | (28.5) | (10.0) |
| TOTAL | 101.6 | 97.8 | 92.5 | 98.9 |

1 Unaltered pillowed metabasaltic lava

2 Weakly altered pillowed metabasaltic lava

3 Strongly altered pillowed metabasaltic lava

4 Weakly albitized pillowed metabasaltic lava

Table 6. Gains and Losses of Cations in the Standard Cell

| SAMPLE TYPE | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Weakly altered pillowed metabasaltic lava | +2.0 | -2.0 | +0.4 | +0.3 | +0.3 | -4.1 | -0.1 | -0.1 | +0.2 | -0.1 |
| Strongly altered pillowed metabasaltic lava | -2.6 | -0.7 | +2.0 | +2.4 | +1.8 | -8.8 | -2.3 | +0.4 | +0.1 | -0.1 |
| Weakly albitized pillowed metabasaltic lava | +2.3 | -0.1 | +0.7 | -1.3 | -2.6 | -4.3 | +2.5 | ±0.0 | +0.1 | ±0.0 |

The strong loss of calcium may be explained by the alteration of the calcic plagioclase, augite, and hornblende to clay, chlorite, zoisite, sericite, biotite, calcite and quartz; the calcium is removed from these minerals as a bicarbonate complex in solution. The progression of alteration from weak to strong shows gains in magnesium mainly as chlorite; gains in iron mainly as pyrite, pyrrhotite or chalcopyrite; slight gains in potassium as sericite or biotite; and strong losses in both silicon (mainly from quartz and feldspars) and sodium (mainly albite). The albitized basalts have undergone a slightly different chemical alteration which is represented mineralogically as a greater increase in albite than chlorite. Like the weakly chloritized rocks, the weakly albitized samples have lost significant calcium and have gained significant magnesium and ferrous iron. This may be accounted for by a gain in quartz, albite, and sulfide minerals at the expense of the mafic minerals such as augite or hornblende in the primary lava flows. The original mineralogy of the altered rocks was overprinted by regional thermal metamorphism, therefore the above discussion on mineralogical changes accompanying alteration is limited to an interpretation of the present mineralogy of the rocks. Although the metamorphic event may have redistributed some of the more volatile elements in the rockmass, the gains and losses of cations in altered rocks compared to unaltered rocks is still valid because both rock types underwent the same degree of metamorphism.

## Rock Alteration and Ore Genesis

In the Anyox massive sulfide deposits, rock alteration patterns provide useful information regarding the geothermal convection system

which was the main mineralizing mechanism. The field distribution of altered rocks is shown in figures 4, 5, 6, 7 and 8. The best chemical data comes from the Hidden Creek deposit, but similar trends hold true for the Double Ed deposit as well.

Silica is enriched in the weakly altered rocks but is depleted in the strongly altered rocks. Quartz veining is greater in the strongly altered zones than in the weaker zones. The sample material from the strongly altered rocks did not include the quartz veins, hence reflects the loss of silica from the basalt to the hydrothermal solutions. The silica enrichment in the weakly altered rocks occurs as scattered quartz grains in the rock matrix and in thin quartz-albite veinlets. The areas of silica enrichment are near the sea floor and represent zones of influx of silica-rich seawater. The net process in the geothermal system was the loss of silica from the basalt to hydrothermal solutions which vented onto the sea floor and mixed with seawater. The silica-enriched seawater recirculated back through the volcanic pile, whereupon the silica precipitated out as the solutions moved through the cold outer layer of the rock mass.

An iron enrichment accompanies all types of rock alteration except the weak albitization of the basalt. The intensely altered basalt contains higher iron contents than the weakly altered varieties. The source of the iron is most likely the basalt itself, which has a high iron content in the form of mafic silicate minerals (augite, hornblende, actinolite), pyrite, pyrrhotite, chalcopyrite, magnetite, ilmenite, maghemite or titanomagnetite. The sulfide and other metallic minerals occur as spotty disseminations or veinlets in the weakly altered rocks

and as disseminations, veinlets and masses several centimeters in diameter in the strongly altered basalt. The opaque minerals mentioned above are the main carriers of iron in the altered rocks and, for the most part, have been introduced into the rock mass. The pyrrhotite in the altered rocks may be in part metamorphic, and is derived from pyrite and the breakdown of iron-rich silicate minerals. The hydrothermal fluids that circulated through the volcanic pile carried a large amount of iron out onto the sea floor where it precipitated as iron sulfide minerals. Thus, a large amount of iron was leached out of the surrounding basalt and fixed in the alteration zones as sulfides and magnetite.

The sulfur, like the iron content of the altered rocks, rises with increasing alteration intensity (see Appendix IV-b). The sulfur in both the altered basalt and massive sulfide bodies is in reduced form as sulfide minerals. Barite, gypsum, or anhydrite are not present in any of the deposits at Anyox. Several sources of sulfur are possible and include seawater sulfate, the volcanic rocks, and magmatic gases and fluids. The source and distribution of the sulfur and its different isotopes are discussed in detail in Chapter VII.

Albitization of the basaltic rocks occurs stratigraphically below the Number 6 deposit at Hidden Creek and in one area underlying a portion of the Double Ed deposit. The albitization in both cases is weak but is distinguished chemically and mineralogically by high sodium values in chemical analyses and anomalous albite contents in the rock mass. The source of the sodium was seawater and may indicate the location where a brine pool fed into a geothermal recharge site. There may be

a relationship between alteration and the geothermal system, because albitization is not widespread either around alteration zones or in unaltered volcanic rocks; at Anyox the two known localities of sodium enrichment are associated with nearby massive sulfide deposits. Sodium-rich brines accompanying weak hydrothermal alteration by low temperature fluids could conceivably produce albitization of the surrounding rock mass.

The study of spatial distribution, intensity, chemistry, and mineralogy of alteration zones has delineated areas that were recharge-discharge sites of hydrothermal fluids during the ore formation event. Indicators of paleo-vent areas are enrichment of iron, magnesium, and sulfur, along with depletion of silica in the volcanic rocks and enrichment of silica as veins and stockwork zones. Areas of sea water influx (hydrothermal fluid recharge sites) are marked by a weak enrichment in silica, iron, magnesium, sulfur, and locally, sodium.

## COPPER GEOCHEMISTRY

### Distribution

Part of the regional exploration program carried out by Cominco Limited in 1976 consisted of analysis of bedrock samples for copper. Over 712 rock samples were collected and analyzed for copper (Osatenko, 1976); additional samples were collected from the vicinity of the Double Ed deposit by the writer, and were also analyzed for copper. Because the population of the Cominco samples was large and because the writer was involved in collecting a large numer of the samples, background and threshold values calculated by Osatenko (1976), using

the cumulative frequency method of Sinclar (1974), have been used in this thesis. The background values reflect typical copper concentrations in barren metabasalt and have an upper limit of 130 parts per million (PPM). Copper contents of over 290 PPM are considered to be anomalous, while values between 130 and 290 PPM are possibly anomalous. The three-fold division of the sample results reflects Sinclar's cumulative frequency method, and actually represents a lower and upper threshold value which helps an exploration geologist to discriminate between first and second order copper anomalies.

A prime concern of this thesis is the distribution of copper in the vicinity of the copper deposits at Anyox. The average value of copper in basaltic rocks is 119 to 123 PPM with a median of 100 PPM for 156 analyses (Prinz, 1968), which agrees with the background values of 0 to 130 PPM for the Anyox metabasalt. Copper geochemical values for metabasalt near the Hidden Creek and Bonanza deposits are shown in figures 4 and 8; similar data for the Double Ed is listed in Appendix V and plotted in figures 5 and 6. The copper values ranged from 5 PPM in barren metabasalt to 10,500 (1.05%) in the mineralized tuffs of the Hidden Creek deposit. At the Hidden Creek deposit, copper content in the metabasalt is proportional to the alteration intensity; the strongly altered basalt has the highest copper values while the unaltered basalt has the lowest. The same pattern of alteration intensity and copper content holds for the Double Ed and Bonanza deposits, but their narrow stratigraphic thickness and the limited areal extent of their associated alteration zones makes this trend less obvious than at the Hidden Creek deposit.

The copper in the metabasalt at Anyox is principally in sulfide form as chalcopyrite. Investigations have not been made to determine the amount of copper in the silicate minerals of the metabasalt. In most Anyox samples that the writer has studied, the copper content corresponds to the observed chalcopyrite content because the two increase or decrease in proportion to one another. Such an observed relationship between copper and chalcopyrite may be fortuitous because the rock samples were digested in hot aqua-regia prior to atomic absorption spectrometric analysis; therefore, this method would not free copper in a silicate mineral. Conversely, a number of samples were analyzed by X-Ray fluorescence spectrometry, which would detect total copper in both sulfide and silicate phases, and values from this method compare with those obtained using the atomic absorption method. The above facts show that only an insignificant amount of copper occurs in the silicate minerals while most occurs as chalcopyrite.

### Source

Tholeiitic basalt is believed to have one of the highest background copper contents of any basalt (Prinz, 1968). The obvious source of copper in the massive sulfide and stockwork deposits then, is the volcanic rocks themselves. Derivation of copper from magmatic gases and fluids is possible and may be an important but minor source compared to the large volume of rocks subjected to hydrothermal alteration. An unmistakable trend of copper enrichment linked with hydrothermal alteration has been established at all three deposits studied at Anyox. A corresponding trend of copper depletion in the metabasalt surrounding

the alteration zones has not been observed, but unless strongly localized, as the copper enrichment is, such a negative copper anomaly is difficult to detect in a large and geochemically variable rock mass.

### Zonation

Zonation of copper is evident at the Hidden Creek deposit where a progressive copper enrichment in the direction of the stockwork and sulfide bodies occurs. The data published by Large (1977) may be used to explain this copper zonation. Copper is carried as chloride complexes in hydrothermal solutions in two types of ore-forming environments, one within the volcanic pile, the other above the seawater-rock interface. The environment within the volcanic pile is dominated by high temperatures ( $270^{\circ}C$) and mildly acidic pH, where $H_2S$ is the principal sulfur species. On the sea floor, the environment ranges from high to low temperature and acid to alkaline pH, where $SO_4^{=}$, $KSO_4^{-}$, or $HSO_4^{-}$ are the principal sulfur species (Large, 1977). After passing from the volcanic pile onto the sea floor, the ore solutions would follow the path A-B in figure 22 (modified after Large, 1977). Point A in figure 22 has an initial temperature of $275^{\circ}C$, pH = 5.0 with a total sulfur content of $10^{-3}$ molar (M). Upon mixing with seawater, the ore solution entered the pyrite-chalcopyrite stability field and then, with decreasing temperature and $fO_2$, it entered the sphalerite field; the minerals precipitated from the solution vary from pyrite to pyrite-chalcopyrite, to pyrite-chalcopyrite-sphalerite assemblages. The ore fluid decreased in temperature and oxygen fugacity with distance from the hydrothermal vents; the fluid passed out of the chalcopyrite and sphalerite stability fields until only pyrite precipitated from solution.

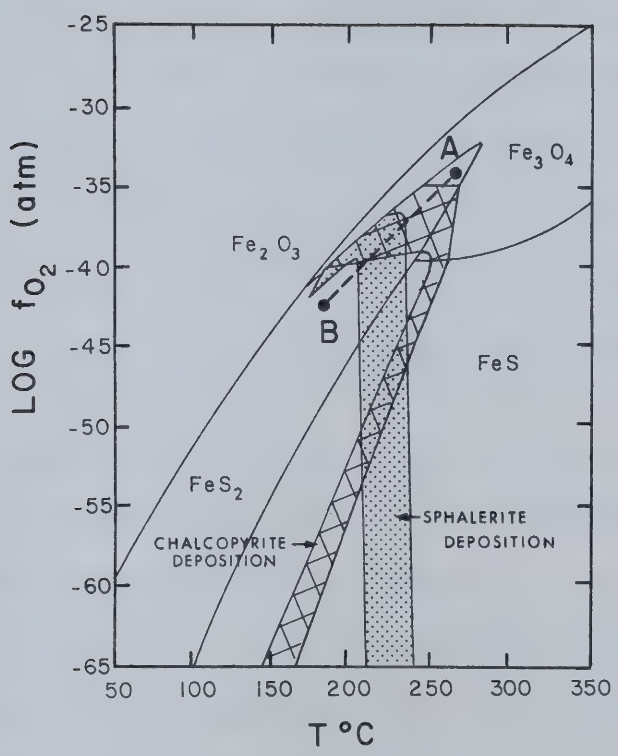



Figure 22. Mixing path in $fO_2$ - T space for Anyox ore fluids (1M NaCl, pH = 5, $\Sigma S = 10^{-3}$ M) (after Large, 1977).

The copper is concentrated in two environments at the Hidden Creek deposit, one in the alteration pipe in the stockwork zones and the second on the sea floor in the proximity of the geothermal vents. The massive sulfide bodies are dominantly pyrite-chalcopyrite, but grade from nearly barren pyrite next to the vent areas to chalcopyrite-pyrite (±sphalerite), and then laterally to barren pyrite. The gradational nature of the copper mineralization may have resulted from changes in temperature and ore fluid chemistry (oxygen fugacity, sulfur fugacity and pH).

## METAL DISPERSION IN EXHALATIVE SEDIMENTS

Metal dispersion on the sea floor away from a mineralized body or an unmineralized active fumarole has been documented by a number of authors (Holmes and Toombs, 1972; Honnorez et. al., 1976: Valette, 1976; Large, 1977; Rona, 1978; Turner and Gustafson, 1978). The Hidden Creek deposit has a well-developed and distinctive volcanic-sedimentary contact, and for this reason it makes a good case study for metal dispersion. A thin to thick bed of quartzite, originally a chert bed, lies along the volcanic-sedimentary contact (see description in Chapter III). The siliceous bed was deposited during the mineralizing event, thus any dispersion of metals away from the sulfide bodies should have a geochemical expression along this horizon. Multiple trace element (Cu, Zn, Pb, Mn, Ba, Ag, Au, and Hg) plus total iron and sulfur analyses were made on a suite of 18 samples from the Hidden Creek deposit. Analytical results are given in Appendix VI and sample locations are shown in figure 4. The material sampled near the sulfide deposits was barren quartzite containing only minor pyrite or pyrrhotite.

The results of the study are inconclusive. The highest copper, zinc, lead, manganese, barium and mercury values were obtained from samples taken in close proximity to the sulfide bodies. Mercury is enriched in the strata near the southwest end of the Number 1 deposit. The cause of the mercury anomaly is unknown but may be related to a later hydrothermal event associated with intrusion of diorite and lamprophyre dikes. Sulfur and iron show weak lateral dispersion patterns away from the massive sulfide deposits.

A marked dispersion of metals away from the sulfide bodies is not apparent from the data on hand. This fact may be real or only apparent, reflecting the relatively limited number of samples taken. Metal dispersion does not appear to be a reliable prospecting tool for indicating blind mineralization at Anyox. Background values of the elements studied do not mean that there is no mineralized body nearby, either along strike or down dip. Whereas background values are not diagnostic, anomalous values may be very significant and should be followed up with additional sampling and prospecting.

## SUMMARY

Major and trace element analyses have been performed on rock samples taken from the Hidden Creek, Double Ed and Bonanza deposits at Anyox. The rocks intimately associated with the massive sulfide deposits are classified as tholeiitic metabasalt, using Irvine and Baragar's (1971) classification scheme. The tectonic environment of extrusion of the original lava (based on trace element data and following Pearce and Gale's 1977 classification) was near a plate

margin on the ocean floor in a back-arc setting similar to the present-day Marianas basin. Alteration of the tholeiitic metabasalt accompanied sulfide formation and was a product of hydrothermal solutions which circulated in an active geothermal system within the volcanic pile. All altered rocks showed a moderate to strong loss in calcium. Strongly altered rocks showed moderate gain in iron, sulfur, and magnesium, but a loss in silica. Weakly altered rocks gained silica, iron, and sulfur. Weakly chloritized rocks gained magnesium and lost sodium, while weakly albitized rocks gained sodium and lost magnesium. Copper content of the altered rocks increases in proportion to the alteration intensity. Metal dispersion along the volcanic-sedimentary contact is poorly developed and is spatially restricted to the proximity of the mineralized areas. Use of metal dispersion as a prospecting tool is limited, but positive anomalies may be significant, while background values are not diagnostic of the presence or absence of nearby mineralization. The geochemistry of the rocks at Anyox can be used as a guide to the genesis of the massive sulfide deposits, the tectonic setting of ore formation, the type of lavas originally extruded, and the presence of nearby sulfide mineralization.

# CHAPTER VII

## SULFUR ISOTOPES

Because of its ability to bond with cations such as iron, copper, lead or zinc, and form stable minerals, sulfur is the dominant element (by atomic proportions) in most massive sulfide deposits. In the Anyox deposits the economic sulfide minerals are chalcopyrite and sphalerite, while the gangue sulfides are pyrite and pyrrhotite. A study of the sulfur isotopes in chalcopyrite, pyrite, and sphalerite taken from each Anyox massive sulfide deposit was undertaken to provide analytical data on mineral genesis. The literature pertaining to sulfur isotopes is voluminous, hence a review of the principles of sulfur isotope geochemistry is beyond the scope of this thesis. The writer's interpretation of the sulfur isotope data is based upon the following references: Bachinski (1977, 1978); Campbell, Ethier, Krouse and Both (1978); Coleman (1977); Kajiwara and Date (1971); Kajiwara and Krouse (1971); Kuo (1976); Ohmoto (1972); Rye and Ohmoto (1974); Sangster (1976); Sasaki (1974); Sasaki and Kajiwara (1971); Thode (1963); Trudinger (1976). The above authors deal with the theory of sulfur isotope geochemistry and discuss its applications to mineral genesis in ore deposits. This chapter covers a brief review of sulfur isotope theory and examines data from the Anyox deposits in the light of current theory.

# THEORY

## Measurement and Reporting of Isotopic Data

The four stable isotopes of sulfur and their abundances were reported by Macnamara and Thode (1950) as: S (mass 32) = 95.02%, S (mass 33) = 0.75%, S (mass 34) = 4.22% and S (mass 36) = 0.02%. The most abundant isotopes of sulfur are those of mass 32 and 34. These isotopes have an actual mass difference of 6%. Isotopic analyses of sulfur measure the ratios of the two most abundant isotopes (mass 32 and 34), using a mass spectrometer. A standard is measured at the same time to produce a reference ratio. The results of the analyses are then reported as "del sulfur (mass 34)" and are expressed in per mil (‰) values. The following formula is used to arrive at the $\delta^{34}S$ (‰) values for each sample measured:

$$(1)\quad \delta^{34}S(\text{sample})(‰) = \frac{(^{34}S/^{32}S)\text{Sample} - (^{34}S/^{32}S)\text{Standard}}{(^{34}S/^{32}S)\text{Standard}} \times 1000$$

A common standard is sulfur obtained from troilite in the Cañon Diablo meteorite, which has a uniform $^{34}S/^{32}S$ ratio of 0.0450045 (Jensen and Nakai, 1963). This standard has been used in most published data and for convenience has been assigned a value of $\delta^{34}S$ ‰ = 0.00. Sulfur from the troilite phase of the Mayerthorpe meteorite has a value of 0.0 ± 0.2 ‰ $\delta^{34}S$ (Sasaki, unpublished research: The University of Alberta), and was used as the meteoritic standard in the writer's research. In equation (1), positive $\delta^{34}S$ values represent an enrichment of sulfur (mass 34) relative to the standard, while negative values represent a depletion of the isotope relative to the standard.

Isotopic Fractionation

Fractionation produces variations in the $^{34}S/^{32}S$ ratios. Urey (1947) showed that as a rule the light isotope forms a weaker bond than the heavy isotope, hence will be more reactive. The two types of isotopic fractionation are equilibrium fractionation, which is governed by bond strength, and kinetic fractionation, which is controlled by the reactivity of the lighter isotope (Coleman, 1977). Equilibrium fractionation is temperature dependent and is most effective at low temperatures; kinetic fractionation is independent of temperature, but is observable only if the products are removed from solution or if the reaction is incomplete.

Kinetic fractionation occurs during the reduction of seawater sulfate to sulfide. The rate of reaction of lighter sulfide anions $^{32}SO_4^{-2}$ is 2.2% faster than the heavier $^{34}SO_4^{-2}$ anion, hence a 22‰ fractionation between the precipitating sulfide and the infinite source of sulfate (i.e. seawater) arises (Coleman, 1977). Kinetic fractionation is important in the reduction of seawater sulfate by the dissimilatory sulfate reducer, *Desulfovibrio desulfuricans* (Trudinger, 1976).

Equilibrium fractionation of sulfur isotopes between co-existing sulfide mineral pairs has been calibrated as a function of temperature by Kajiwara and Krouse (1971) and may be used as a geothermometer. Ohmoto (1972) further expanded Sakai's (1968) work on equilibrium fractionation and showed that in ore solutions, fractionation of sulfur isotopes occurs between precipitating sulfide or sulfate minerals and the species $H_2S$, $HS^-$, $S^{-2}$, $HSO_4^-$, $KSO_4^-$, and $NaSO_4^-$ in

solution. The aforementioned species occur in restricted pH and oxygen fugacity conditions, and from their equilibrium fractionation constants, Ohmoto (1972) was able to construct diagrams of oxygen fugacity versus pH for systems of known temperature, ionic strength and $\delta^{34}S_{\Sigma S}$. These diagrams, with the $\delta^{34}S_i$ contours and Fe-S-O mineral stability fields plotted on them, show that small changes in either pH or $fO_2$ can produce large fractionations of sulfur isotopes. The recognition of pH and oxygen fugacity-controlled equilibrium fractionation led to re-evaluation of previous interpretations of sulfur isotopic data, which suggested that values near 0‰ indicate a magmatic source of sulfur, and scattered, broadly ranging values indicate a bacteriogenic origin of sulfur (Jensen, 1967). Rye and Ohmoto (1974) have shown that sulfur isotope distributions produced by bacterial sources may have either a wide or narrow range, depending on whether the geothermal system or marine basin was open or closed.

In the study of sulfur isotope distribution at Anyox, the isotopic fractionation mechanism for sulfur in each ore deposit influences the interpretation of the genesis of the massive sulfide bodies. In an active geothermal environment, equilibrium fractionation of sulfur isotopes is likely to dominate the system, therefore interpretations of the isotopic distributions using the principles established by Kajiwara and Krouse (1971), Ohmoto (1972), Rye and Ohmoto (1974), and Sangster (1976) are applicable. The following sections are devoted to the presentation, discussion and interpretation of the sulfur isotopes in the Anyox massive sulfide deposits.

## RESULTS

In order to establish relationships between sulfide-sulfide and sulfide-silicate minerals, the material sampled for sulfur isotopic analysis was studied in outcrop, drill core, hand specimen slabs, and in polished section. The mineralogy is a simple assemblage of pyrite $>$ pyrrhotite $\gg$ chalcopyrite $>$ sphalerite $\gg$ arsenopyrite. The sulfide assemblages were metamorphosed to the upper greenschist facies of regional metamorphism and were deformed during two phases of folding that affected the area. Tertiary dike swarms transect the deposits, but visible thermal effects appear to be limited to 0.5 m from the dikes.

Polished sections of samples taken from the massive sulfide zones commonly show that pyrite has recrystallized into euhedral crystals, chalcopyrite has flowed plastically around other more brittle mineral grains, and that pyrrhotite occurs either as isolated anhydral grains often associated with chalcopyrite or as massive aggregates with blebs of chalcopyrite. Occasional grains of sphalerite are present in the pyrite-quartz-rich sections of the orebodies; sphalerite also occurs in massive lenses. Small grains of chalcopyrite are found in the massive sphalerite layers; sphalerite grains commonly contain blebs of chalcopyrite (which may be exsolution textures). Galena is present in late quartz veins that cut through the argillite above the deposits, but is noticeably absent in the massive sulfide bodies. No galena has been recognized in polished sections from the ore zone. Traces of arsenopyrite have been recognized in some polished sections, but this mineral is rare. Notable textures are: (1) the euhedral pyrite

crystals which often show granulation due to deformation and (2) the bird's eye texture of pyrrhotite, which is attributed to alteration caused by surface weathering. Two types of pyrrhotite, monoclinic and hexagonal, are present in the deposits, but their distribution was not studied in detail.

### Sulfide Sample Selection

Representative sulfide samples were taken from different levels in the stratigraphic columns in each of the massive sulfide deposits. All samples from the Double Ed deposit were obtained from diamond drill core; samples at Hidden Creek were taken from drill core and surface outcrop; samples at the Bonanza deposit were gathered from the walls of the glory hole. Samples were selected for isotopic analysis so that a pattern of sulfur isotope distribution could be studied both vertically and laterally through each deposit. Only fresh sulfides were analyzed; samples showing more than one generation of sulfide minerals were omitted. A complete description of sample preparation and analysis is given in Appendix VII-a and VII-b.

### Analytical Results

Results from mass spectrometric analyses of the prepared $SO_2$ gas samples are listed in Appendix VII-d. Yield data obtained during the oxidation of the sulfide to $SO_2$ gas is included for each sample. It is important that yields be near 100% to insure that no fractionation occurred during the preparation of the $SO_2$ gas. Yields shown are usually better than 93%, but several are less than 90%. Standard samples collected during the course of the $SO_2$ gas preparation are

listed in Appendix VII-c and show no fractionation induced during sulfide gassification. Low yields are attributed to tiny quartz grains, intergrown with the pyrite, which interfere with true sulfide sample weight calculations and tend to produce lower actual yield values than theoretically expected. All samples were optically examined and hand-picked to greater than 98% purity before gassification. Trace amounts of pyrite and pyrrhotite intergrown with the chalcopyrite grains may have produced higher than expected yields during the chalcopyrite gassification step. The problem of impurities in fine-grained sulfide samples may be overcome by reacting the sample with acid to release hydrogen sulfide, which may then be precipitated as cadmium or silver sulfide and oxidized to sulfur dioxide. Facilities for such a process are not available at the University of Alberta, therefore direct oxidation of the sulfide sample was used.

The mean ‰ value of $\delta^{34}S$ of the sulfide samples analyzed from each deposit at Anyox is listed in Table 7. All three deposits are enriched in sulfur (mass 34) with respect to the meteoritic standard. The sulfur in the sulfide minerals in the stockwork deposit (feeder pipe) that underlies the Hidden Creek stratiform orebody is most strongly enriched in sulfur of mass 34 (+10.0‰ $\delta^{34}S$ pyrite, +8.48‰ $\delta^{34}S$ chalcopyrite). The stratiform deposits contain slight enrichments of $\delta^{34}S$ in pyrite; mean $\delta^{34}S$ values in pyrite are +4.19‰ (Double Ed), +2.85‰ (Hidden Creek), +1.52‰ (Bonanza). Sulfur isotope values of both chalcopyrite and sphalerite, in each deposit, follow the trend of the pyrite values.

Table 7. $\delta^{34}S$ Distribution of Anyox Massive Sulfide Deposits

| DEPOSIT | | PYRITE (‰) | CHALCOPYRITE (‰) | SPHALERITE (‰) |
|---|---|---|---|---|
| Double Ed | Mean | +4.2 | +3.5 | +2.4 |
| | Range | +2.0 to +4.9 | +2.7 to +4.3 | - |
| | No. Samples | 21 | 9 | 1 |
| Hidden Creek Stockwork Zones | Mean | +10.0 | +8.5 | - |
| | Range | - | +7.6 to +9.8 | - |
| | No. Samples | 1 | 4 | - |
| Hidden Creek Stratiform Sulfides | Mean | +2.8 | +2.8 | - |
| | Range | -4.3 to +6.7 | -3.3 to +6.2 | - |
| | No. Samples | 4 | 3 | - |
| Bonanza | Mean | +1.5 | +1.4 | +1.2 |
| | Range | +0.2 to +2.4 | - | - |
| | No. Samples | 4 | 1 | 1 |

# INTERPRETATION OF RESULTS

## Sulfur Isotope Distribution

Figure 23 shows the range of the sulfur isotopic data from Anyox and compares them with similar data from Newfoundland, Cyprus (Bachinski, 1977), and the Kuroko (Rye and Ohmoto, 1974), Løkken (Plimer and Finlow-Bates, 1978), and Besshi (Kajiwara and Date, 1971) deposits. The spread in values is greatest for the Hidden Creek deposit and is comparable to the range of the Kuroko data. Sulfur isotopes from sulfides at both the Double Ed and Bonanza deposits have a small spread, and have distributions similar to those from the Whalesback and Gull Pond (Newfoundland), Løkken (Norway), and Besshi (Japan) deposits. The above comparisons are based solely on the isotopic values and their range; as Rye and Ohmoto (1974, p. 827) point out, "one cannot classify the types of ore deposits or say very much about their genesis on the basis of sulfur isotope values alone."

## Effects of Metamorphism

The rocks at Anyox have been subjected to burial and regional thermal metamorphism in the greenschist facies temperature and pressure range (350 to 500°C and 2 to 8 kilobars) (Winkler, 1974). Contact metamorphism produced by Tertiary dike swarms also affected the deposits. The sulfide minerals were affected by the metamorphic events described earlier; they recrystallized and underwent either plastic or brittle deformation. Metamorphic pyrrhotite formed when pyrite grains reacted with iron-rich silicate minerals in the metabasaltic or metasedimentary rocks. Such metamorphic events influence sulfur isotope values and distributions in the massive sulfide deposits at Anyox.

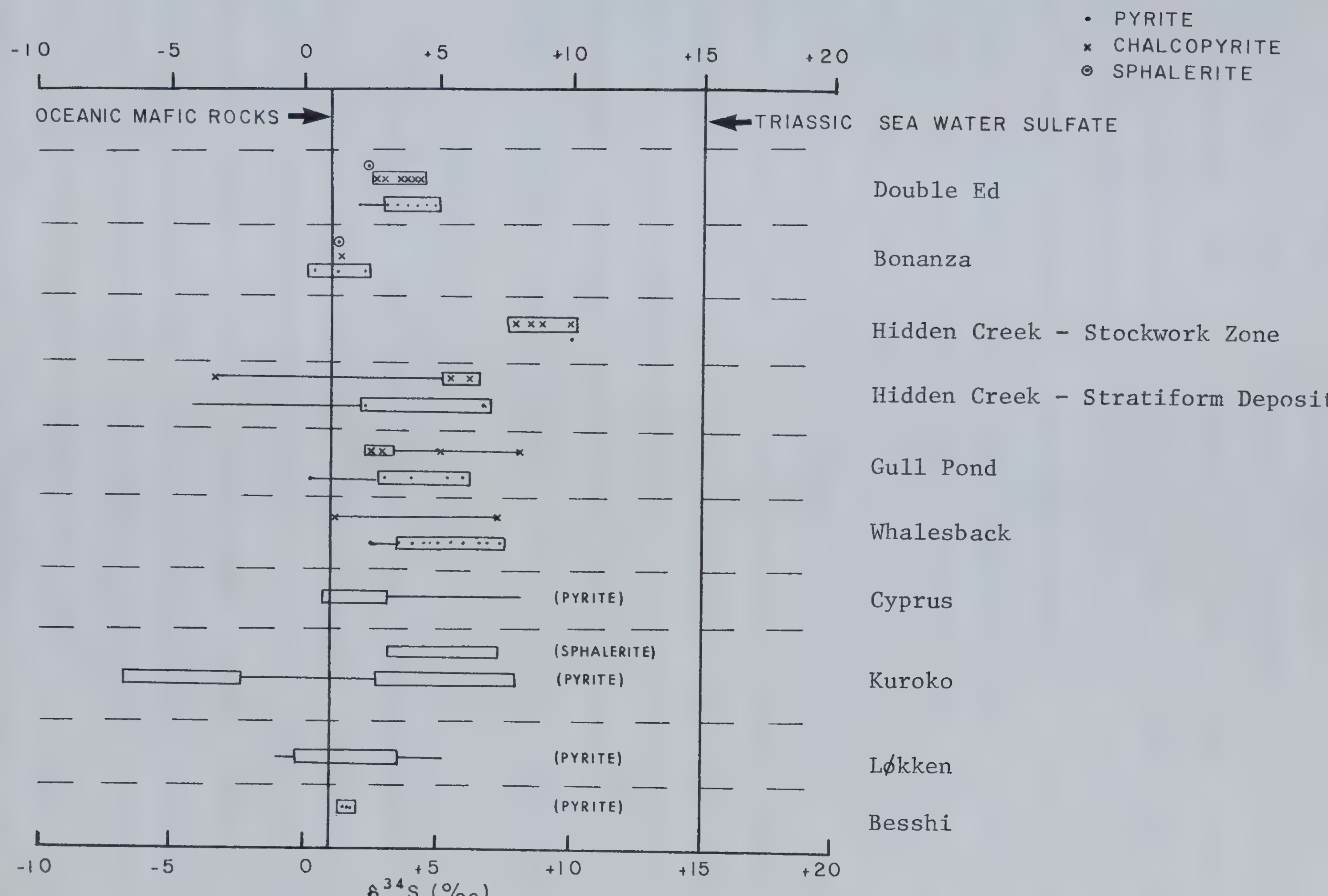



Figure 23. Sulfur isotope composition in cupriferous iron sulfide deposits (Gull Pond, Whalesback, Cyprus data from Bachinski, 1977, 1978; Kuroko data from Rye and Ohmoto, 1974; Løkken data from Plimer and Finlow-Bates, 1978; Besshi data from Kajiwara and Date, 1971).

It is currently believed that metamorphism of stratiform sulfide deposits does not destroy large-scale premetamorphic $\delta^{34}S$ variations (Rye and Ohmoto, 1974). The average $\delta^{34}S$ values for the sulfide minerals remain unchanged in major rock units, but small-scale variations are overprinted on the original isotopic distribution. The small-scale changes are caused by redistribution of sulfur isotopes amongst co-existing sulfide minerals and the metamorphic fluid. Equilibrium fractionation in such a closed system would most likely be preserved. Kinetic fractionation would also occur but would not be preserved unless the system was open, thus permitting the metamorphic fluids to remove significant amounts of sulfur (mass 32) from the sulfide zones, resulting in a relative increase in heavy sulfur (mass 34) within the deposit. What is preserved at Anyox is a record of the metamorphic temperatures, the original mean sulfur isotopic distribution in each deposit, and small-scale $\delta^{34}S$ variations produced by metamorphism.

### Geothermometry

The details of quantitative sulfur isotope geothermometry were worked out by Rye and Czamanske (1969) and Kajiwara and Krouse (1971), who showed that equilibrium fractionation of sulfur isotopes between co-existing sulfide minerals is temperature dependent. Figure 24 (after Rye and Ohmoto, 1974) illustrates the isotopic enrichment factors among sulfur species and hydrothermal minerals at different temperatures and shows that isotopic fractionation decreases with an increase in temperature. The best geothermometer mineral pairs are those which have the largest fractionation between sulfur isotopes, for a

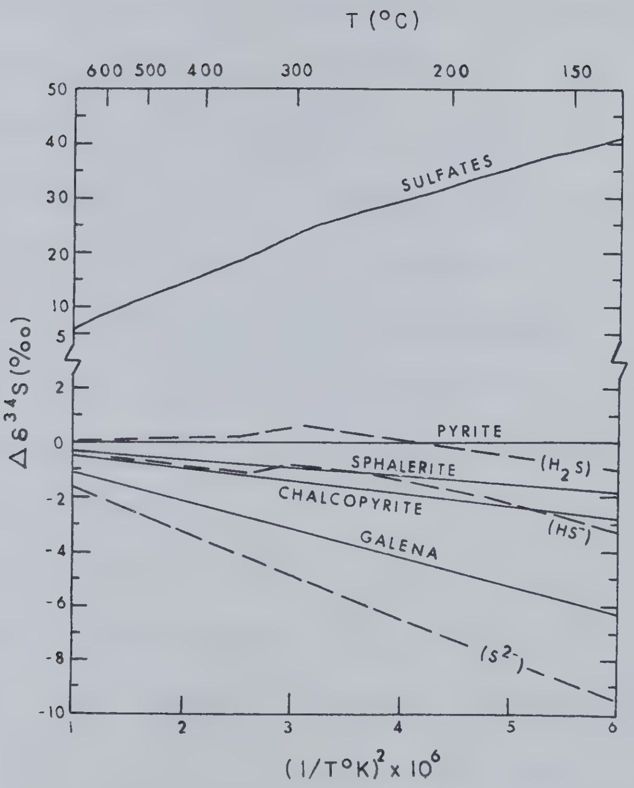



Figure 24. Sulfur isotope fractionations among sulfur species and hydrothermal minerals plotted with respect to pyrite (after Rye and Ohmoto, 1974).

temperature range between room temperature and 800°C; they are sulfate-sulfide pairs followed by sulfide-sulfide pairs. Because no sulfate minerals or galena are found in the massive sulfide deposits at Anyox, only pyrite, sphalerite, pyrrhotite, and chalcopyrite pairs may be used as geothermometers. Pyrrhotite was not analyzed because of sample purity problems and sphalerite was not present in most samples, thus pyrite-chalcopyrite pairs were used to provide most of the temperature data from the deposits. To be useful as a geothermometer, the pyrite-chalcopyrite pair must have formed in equilibrium with solutions that were of uniform temperature and chemical states, such as $\delta^{34}S_{\Sigma S}$, pH and $fO_2$ (Rye and Ohmoto, 1974).

Sulfur isotopes of mineral pairs that form in equilibrium from a solution will provide data which can be used to calculate their temperature of formation. If a deposit has not been metamorphosed, then the calculated temperature will indicate the temperature at which the sulfide pairs were deposited from the original ore-bearing solutions. At Anyox, regional metamorphism reached upper greenschist grades and caused a re-equilibration of sulfur isotopes between sulfide pairs; the sulfur isotopes reflect the thermal history of the metamorphic event and not the primary temperature of formation. A similar over-printing has affected temperature calculations from sulfur isotopes of sulfides taken from the Sullivan mine, British Columbia (Campbell et. al., 1978; Ethier et. al., 1976).

Table 8 lists the $\Delta\delta^{34}S$ (‰) values and the calculated temperatures of formation for each sulfide pair from the Anyox deposits. These temperatures are calculated using the equations published by Kajiwara and

Table 8. Sulfur Isotope Temperature Pairs

| SAMPLE NUMBER | DEPOSIT | PAIR | $\Delta\delta^{34}S$ | TEMPERATURE (°C) |
|---|---|---|---|---|
| U2-243 | Double Ed | Pyrite-Chalcopyrite | 1.2 | 339 |
| U2-262 | Double Ed | Pyrite-Chalcopyrite | 0.6 | 593 |
| U2-295 | Double Ed | Pyrite-Chalcopyrite | 0.3 | 952 |
| U2-360 | Double Ed | Pyrite-Chalcopyrite | 0.4 | 788 |
| U13-76 | Double Ed | Chalcopyrite-Sphalerite | 0.6 | 227 |
| U13-157 | Double Ed | Pyrite-Chalcopyrite | 1.0 | 398 |
| U13-166 | Double Ed | Pyrite-Chalcopyrite | 0.9 | 434 |
| U13-214 | Double Ed | Pyrite-Chalcopyrite | 0.8 | 477 |
| U13-253 | Double Ed | Pyrite-Chalcopyrite | 0.8 | 477 |
| HC-2 | Hidden Creek | Pyrite-Chalcopyrite | 0.2 | 1227 |
| HC-7 | Hidden Creek | Pyrite-Chalcopyrite | 1.3 | 315 |
| HC-8 | Hidden Creek | Pyrite-Chalcopyrite | 0.5 | 676 |
| SR-70 | Bonanza | Pyrite-Sphalerite | 1.1 | 249 |
| SR-72b | Bonanza | Pyrite-Chalcopyrite | 0.8 | 477 |

Krouse (1971):

$$\delta^{34}S \text{ pyrite-chalcopyrite} = 4.5 \times 10^5/T(^\circ K)^2$$

$$\delta^{34}S \text{ pyrite-sphalerite} = 3.0 \times 10^5/T(^\circ K)^2$$

$$\delta^{34}S \text{ sphalerite-chalcopyrite} = 1.5 \times 10^5/T(^\circ K)^2.$$

Temperatures obtained for the U2-295 and HC-2 sulfide pairs are very high (greater than 950°C) and may represent either disequilibrium conditions between sulfide pairs, or the temperature of late Tertiary dikes emplaced nearby. The Double Ed data showed temperature ranges between 227°C and 952°C. Excluding the anomalously high values (952° and 778°C), the average temperature is 421°C; for a pyrite-chalcopyrite pair at this temperature, the analytical uncertainty is ±76°C, which means that the actual temperature of formation may fall anywhere between 357° and 510°C. This temperature range corresponds to that commonly associated with greenschist metamorphic grades and supports the hypothesis that temperatures indicated by the sulfide pairs are metamorphic and not primary temperatures of formation. Temperatures of 400°C are uncommon on the sea floor, especially away from hydrothermal vents, although temperatures as high as 615°C have been reported in fumaroles at Vulcano, Eolian Islands, by Honnorez et. al. (1976). The lowest temperatures at Anyox are given by the chalcopyrite-sphalerite and pyrite-sphalerite mineral pairs and are 227°C and 249°C, respectively. These temperatures are significantly lower than those calculated from pyrite-chalcopyrite pairs; possible explanations are that: (i) the pairs are not equilibrium assemblages; (ii) the pairs are equilibrium assemblages which reflect the primary temperature of formation; (iii) the pairs are equilibrium assemblages which reflect the temperature at

which partitioning between the minerals ceased during the falling temperatures of metamorphism. Of the three choices, (iii) is the preferred explanation because the entire area was subjected to significant thermal metamorphism, which would overprint original isotopic temperature distributions. It is possible that fractionation processes between sphalerite and either pyrite or chalcopyrite were active at lower temperatures than similar processes for pyrite-chalcopyrite pairs. Sphalerite-sulfide pairs tend to yield the lowest temperatures of formation.

Figure 25 is a plot of $\delta^{34}S$ versus $\Delta\delta^{34}S$ for the Double Ed and Hidden Creek deposits. This figure shows that the mean $\delta^{34}S$ value of the sulfur species in solution during sulfide formation was between +3.2 and +5.05‰ for the Double Ed deposit, and was +6.7‰ for the Hidden Creek deposit. The metamorphic event caused a period of isotope exchange during deformation and recrystallization of the pyrite, chalcopyrite and sphalerite minerals. The range of $\delta^{34}S$ shown in figure 25 reflects the $\delta^{34}S$ values of the sulfur species in the metamorphic fluid and does not reflect the values of the original ore solution (+15‰ $\delta^{34}S$ for coeval Upper Triassic seawater sulfate).

The data from the Double Ed suggests that there were two periods of sulfide formation or sulfur isotope re-equilibration. One such period occurred between the high temperatures of 788 and 952°C. At this temperature range, the sulfur species in solution had a mean $\delta^{34}S$ value of +3.2‰. A lower temperature period between 339 and 593°C is also recognizable; sulfur isotope exchange between the sulfur species in the metamorphic fluid (with a mean $\delta^{34}S$ value near +5.0‰) and the

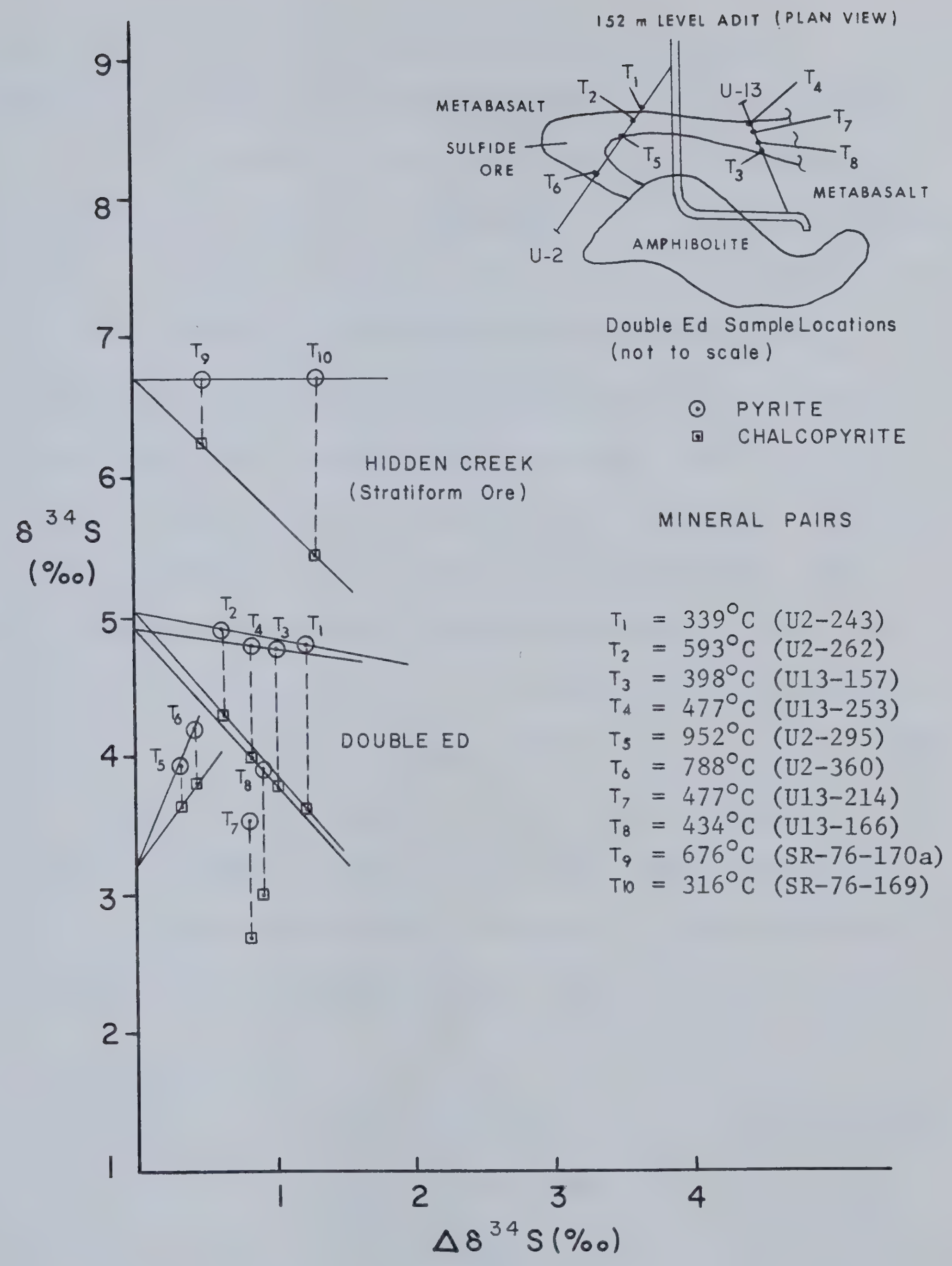



Figure 25. Mean $\delta^{34}S$ values of sulfur species in solution during sulfide mineral formation at the Double Ed and Hidden Creek deposits.

sulfide minerals in the deposit occurred at this temperature. The range of temperature data from the sulfur isotope pairs may be explained in two ways. One explanation is that sulfur isotope partitioning between sulfur minerals and sulfur in the metamorphic fluid occurred at varying temperatures; a similar partitioning could have occurred between pyrite and chalcopyrite in dry or impermeable zones of the ore deposits. A second explanation for the wide temperature range of the pyrite-chalcopyrite geothermometer is that two discrete thermal events occurred, one the metamorphic event, as described previously, the other a localized thermal high accompanying the intrusion of a dike or plug. Small intrusive bodies, such as diorite dikes and amphibolite plugs, are known to cut the Anyox orebodies in many places and would undoubtedly have some effect on the sulfur isotopic distribution of nearby sulfide minerals. Thus, the sulfide-sulfide geothermometer is useful only as an indicator of metamorphic temperatures of the Anyox massive sulfide deposits; the primary temperatures of formation of the sulfide minerals on the sea floor must be estimated using other criteria.

### Source of Sulfur

A large amount of sulfur was supplied to the mineralizing systems in the Anyox deposits. The Hidden Creek deposit alone contained at least 18 million tonnes of sulfide minerals (excluding gangue) in the stratiform layer and underlying alteration zone. The sulfides are mixtures of pyrite, pyrrhotite, chalcopyrite, and sphalerite, therefore the weight of sulfur would be about 8.12 million tonnes (8.12 billion kilograms).

There are two possible sources of sulfur in any submarine volcanic terrain. One source is seawater sulfate and the other is magmatic sulfur. The isotopic value of sulfur from each source is markedly different; seawater has a present day $\delta^{34}S$ value of +21‰ and magmatic sulfur has a value of 0‰ (Sangster, 1976). The $\delta^{34}S$ value of seawater is known to have varied throughout the Phanerozoic and was about +15‰ during the Triassic period when the Anyox sulfide deposits formed. Sulfur isotopic values of precipitated sulfide minerals are dependent on the isotopic values of the sulfur reservoir and interpretation of sulfur isotope data from any submarine volcanogenic massive sulfide deposit must take into account the isotopic value of the reservoir sulfur. Under identical $fO_2$ - pH and temperature conditions, very different $\delta^{34}S$ values for the sulfur isotopes of precipitating sulfides can by obtained by changing the $\delta^{34}S$ value of the source sulfur (Rye and Ohmoto, 1974). As will be discussed in following sections, the average of the sulfur in the Anyox deposits is heavier than the average sulfur in most volcanogenic deposits, and the time-space distribution of the isotopes indicates the sulfur came from a reservoir of constant isotopic composition. These factors suggest a seawater dominated sulfur source with only minor contributions from a magmatic source.

If seawater sulfate was the source of sulfur at Anyox, then a mechanism must have operated to reduce the sulfur to a state in which it could bond with cations to form sulfide minerals. Sulfate contained in seawater that is circulated through a hot volcanic pile is reduced and fractionated at hydrothermal temperatures (above 150°C) by variations

in pH and oxygen fugacity of the fluid system (Ohmoto, 1972; Rye and Ohmoto, 1974). An alteration zone is associated with each of the massive sulfide deposits studied at Anyox; it is thus possible that the fractionation processes described above were operative during ore formation. Hydrothermal temperatures in the geothermal system and near fumaroles tend to rule out the significance of bacteriological reduction of seawater sulfate as an important mechanism.

The fractionation factor, $\Delta(\delta^{34}S)$, is a measure of the degree of fractionation between sulfur isotopes in massive sulfide deposits and those in the sulfate in the coeval sea. It is calculated as follows (Sangster, 1976):

$$\Delta(\delta^{34}S) = \delta^{34}S(\text{Seawater}) - \delta^{34}S(\text{Mean for Deposit})$$

Mean $\delta^{34}S$ values for the deposits in the Anyox area were calculated statistically for the Double Ed, but not for the Hidden Creek or Bonanza orebodies because of limited data on the latter two. This statistical method used by Sangster for calculating the mean $\delta^{34}S$ values from 110 stratabound sulfide deposits calls for rejection of values that fall outside two standard deviations from the mean, followed by a recalculation of the data until all values are within this limit. Such a method is used only if 10 or more analyses of sulfur isotopes were made on each deposit, and is intended to remove erratic values from the data; this method was used to treat the Double Ed data. The mean values of the sulfur isotopes in the Anyox deposits are shown in Table 9. If the deposits at Anyox are Upper Triassic, then the $\delta^{34}S$ value of the sulfate in the ocean was +15‰. The fractionation factors for each deposit, using the data from Table 9 and the

Table 9. Sulfur Isotope Means for the Anyox Massive Sulfide Deposits

| DEPOSIT | NUMBER OF SAMPLES | MEAN ($\delta^{34}S$‰) |
|---|---|---|
| Double Ed | 28 | +4.1 |
| Hidden Creek | 12 | +5.3 |
| Bonanza | 6 | +1.4 |

value of +15‰ $\delta^{34}S$, have been calculated and are given in Table 10. The data from Table 10 is plotted in figure 26 along with the mean $\delta^{34}S$ values calculated for sedimentary and volcanic ores by Sangster (1976). The fractionation factor for each of the Anyox deposits differs slightly; this difference may be more apparent than real because of the limited sulfur isotope data from the Hidden Creek and Bonanza deposits. The mean values of the fractionation factors for each Anyox deposit fall within the range of mean values associated with other deposits in volcanic rocks; they also fall within the range of bacterial fractionation of seawater sulfate. The sulfur isotopes from the Double Ed and Bonanza deposits show a tight grouping (see figure 23), whereas they show a wide spread at the Hidden Creek deposit. The tight grouping suggests a uniform source of sulfur and uniform temperature, $fO_2$, and pH conditions during sulfide formation: the wide spread may be explained by a uniform sulfur source but varying physico-chemical conditions in time and space.

During the formation of the Anyox massive sulfide deposits, seawater sulfate provided a source of sulfur for the formation of sulfide minerals. Reduction of the seawater sulfate was mainly physico-chemical at all three deposits studied. The problems of disequilibrium and survival of bacteria in hot brine areas associated with the massive sulfide deposits makes it appear unlikely that the Double Ed or Bonanza deposits, which have a narrow isotopic distribution, contain bacteriogenic sulfides.

### Time and Space Variations of $\delta^{34}S$

Time and space variations of $\delta^{34}S$ values within the Anyox massive sulfide deposits are shown in figure 27. Similar variations in $\delta^{34}S$

Table 10. Fractionation Factors for the Anyox Massive Sulfide Deposits

| DEPOSIT | $\delta^{34}S$ (‰) |
|---|---|
| Double Ed | +10.9 |
| Hidden Creek | + 9.7 |
| Bonanza | +13.6 |
| Composite Average | +11.4 |

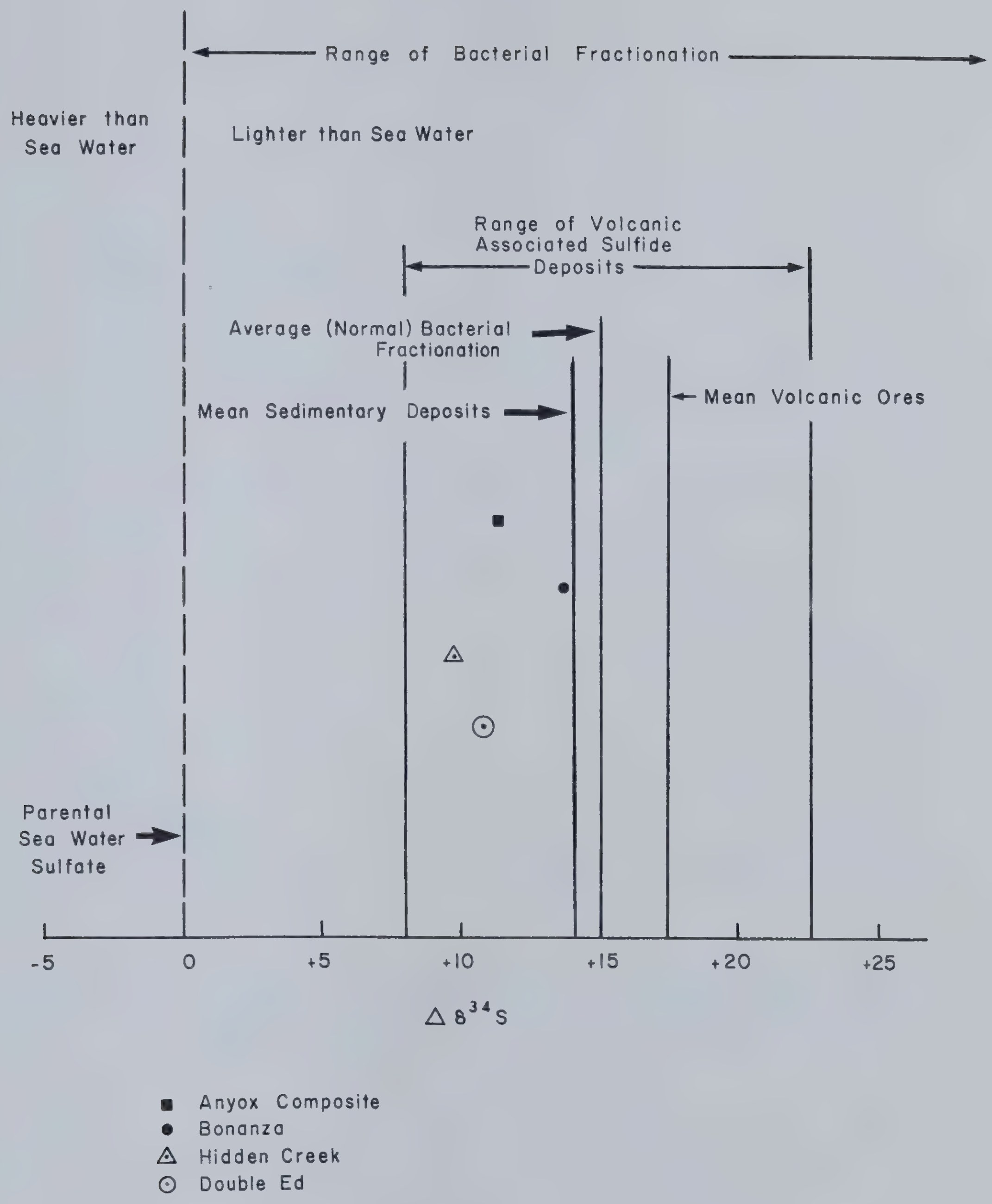



Figure 26. Range and mean of $\Delta(\delta^{34}S)$ values in stratbound sulfide deposits enclosed in marine host rocks (after Sangster, 1976).

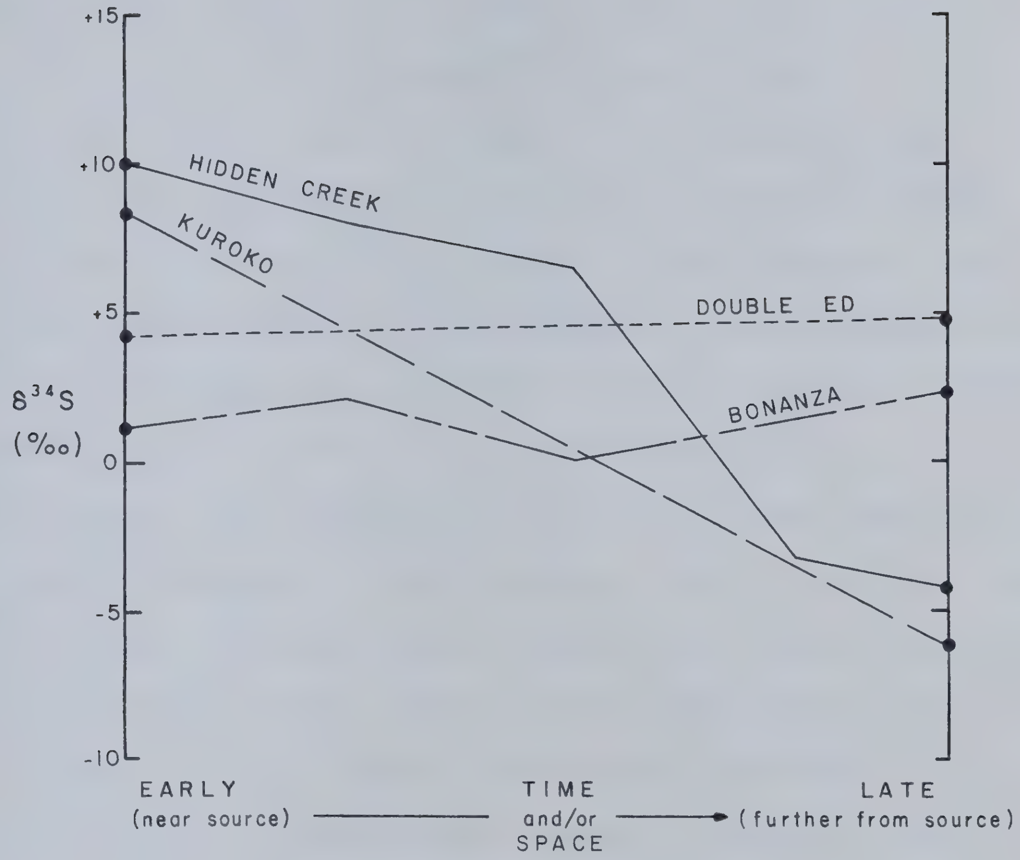



Figure 27. Trends of pyrite $\delta^{34}S$ values in time and/or space for Anyox and Kuroko deposits (Kuroko data from Sasaki, 1974).

values of the Kuroko deposits (after Sasakai, 1974) are plotted for comparison. The Double Ed and Bonanza deposits have only minor variations in $\delta^{34}S$ values, but the Hidden Creek and Kuroko deposits show a distinct trend of decreasing $\delta^{34}S$ in time and space. Stratigraphic columns of the Double Ed (figures 28 and 29), Hidden Creek (figure 30), and Bonanza (figure 31) deposits illustrate $\delta^{34}S$ variations in time, space and bedrock lithology. If the large-scale premetamorphic distributions of $\delta^{34}S$ are preserved in each deposit, then figures 28 to 31 suggest that the physico-chemical conditions of sulfide formation were nearly uniform during formation of the Double Ed and Bonanza deposits, but varied significantly for the Hidden Creek deposit.

During the formation of the hydrothermal sulfide minerals in each deposit at Anyox, the sulfur isotope composition was controlled by the temperature, $\delta^{34}S_{\Sigma S}$, the pH, and the relative proportions of oxidized versus reduced species of sulfur in solution (Rye and Ohmoto, 1974). Diagrams of pH versus oxygen fugacity for a given temperature were constructed (after Ohmoto, 1972) to help interpret possible physico-chemical changes in space or time in the Anyox deposits. On the basis of known temperatures of formation for other volcanogenic massive sulfide deposits, a temperature of 250°C was selected for the ore solution that formed the Anyox stratiform sulfide bodies. The source of the sulfur was taken as Triassic seawater sulfate, with an isotopic composition of +15‰ $\delta^{34}S$.

Several diagrams of oxygen fugacity versus pH are included to show the depositional environment of the Hidden Creek (figure 32), Double Ed (figure 33), and Bonanza (figure 34) massive sulfide layers. The

## LEGEND

| | |
|---|---|
| 5 | Argillite (quartzo-feldspathic and pelitic metasediments) |
| 4 | Dikes |
| | 4A Diorite |
| | 4B Lamprophyre |
| | 4C Felsite |
| | 4D Amphibolite |
| 3 | Massive Sulfides: pyrite, pyrrhotite, and chalcopyrite, minor sphalerite |
| 2 | Mixed Metapelitic Rocks and Metabasaltic Tuff |
| | 2A Tuff more abundant than metapelite |
| | 2B Metapelite more abundant than tuff |
| 1 | Metabasalt |
| | 1A Pillowed flows, locally massive |
| | 1B Agglomerate |
| | 1C Tuff |
| | 1D Fragmental: Tectonic breccia, may include some agglomerate |

## SYMBOLS

● Pyrite Sulfur Isotope Ratio

△ Chalcopyrite Sulfur Isotope Ratio

x Sphalerite Sulfur Isotope Ratio

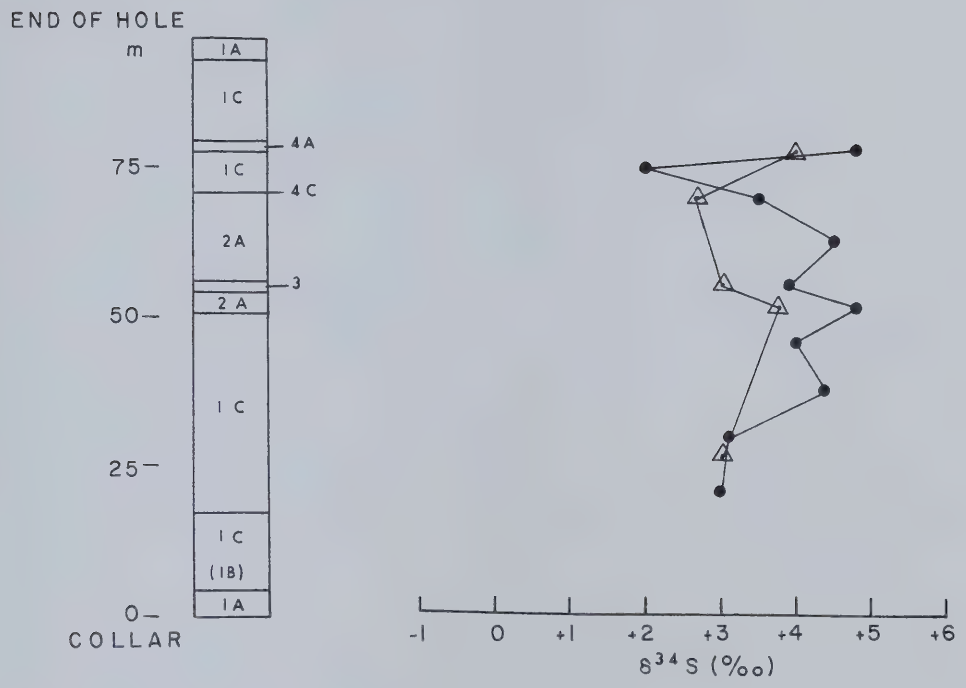



Figure 28. Sulfur isotope variations in time, space, and bedrock lithology in diamond drill hole U-13, Double Ed deposit.

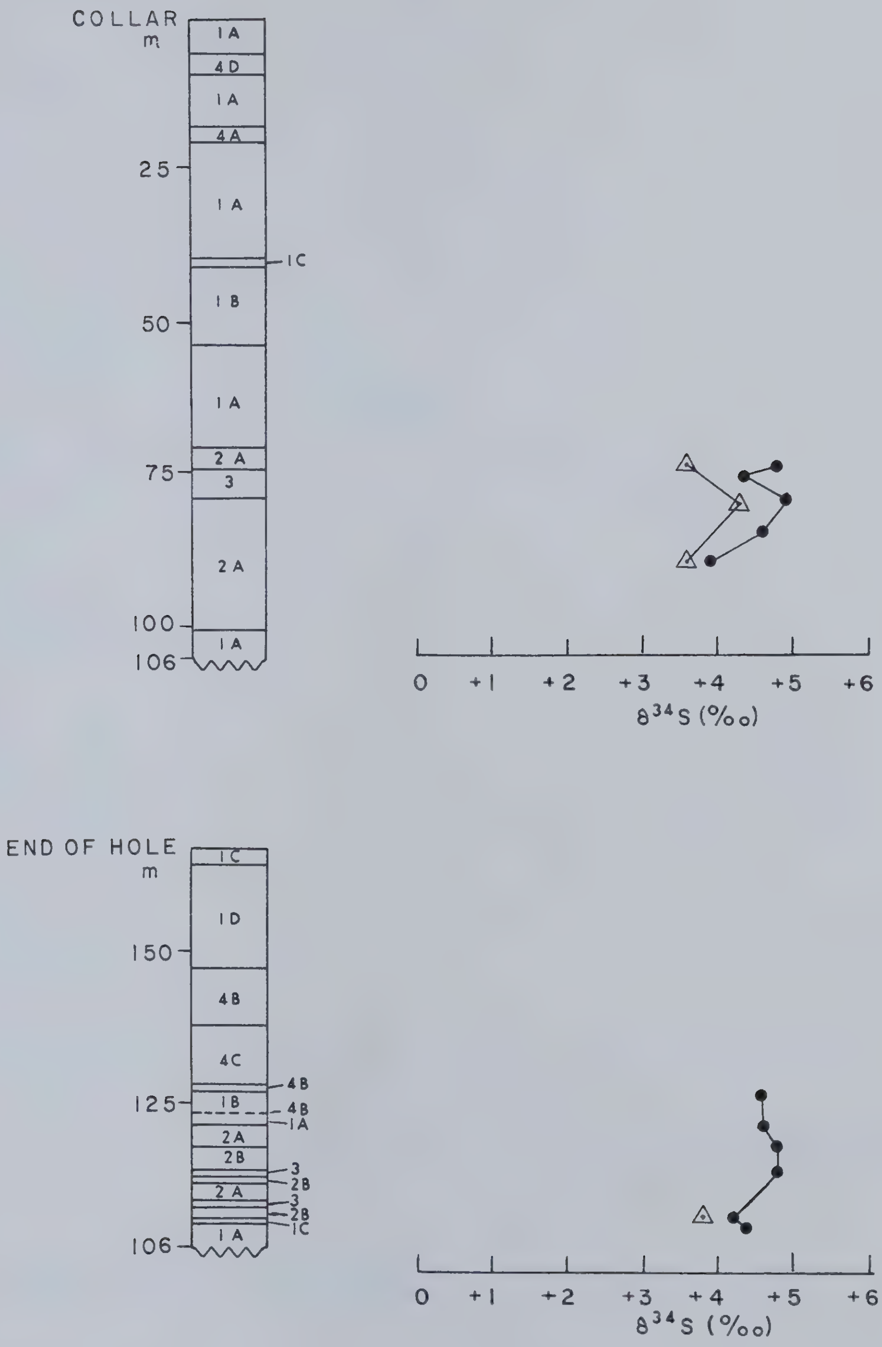



Figure 29. Sulfur isotope variations in time, space, and bedrock lithology in diamond drill hole U-2, Double Ed deposit.

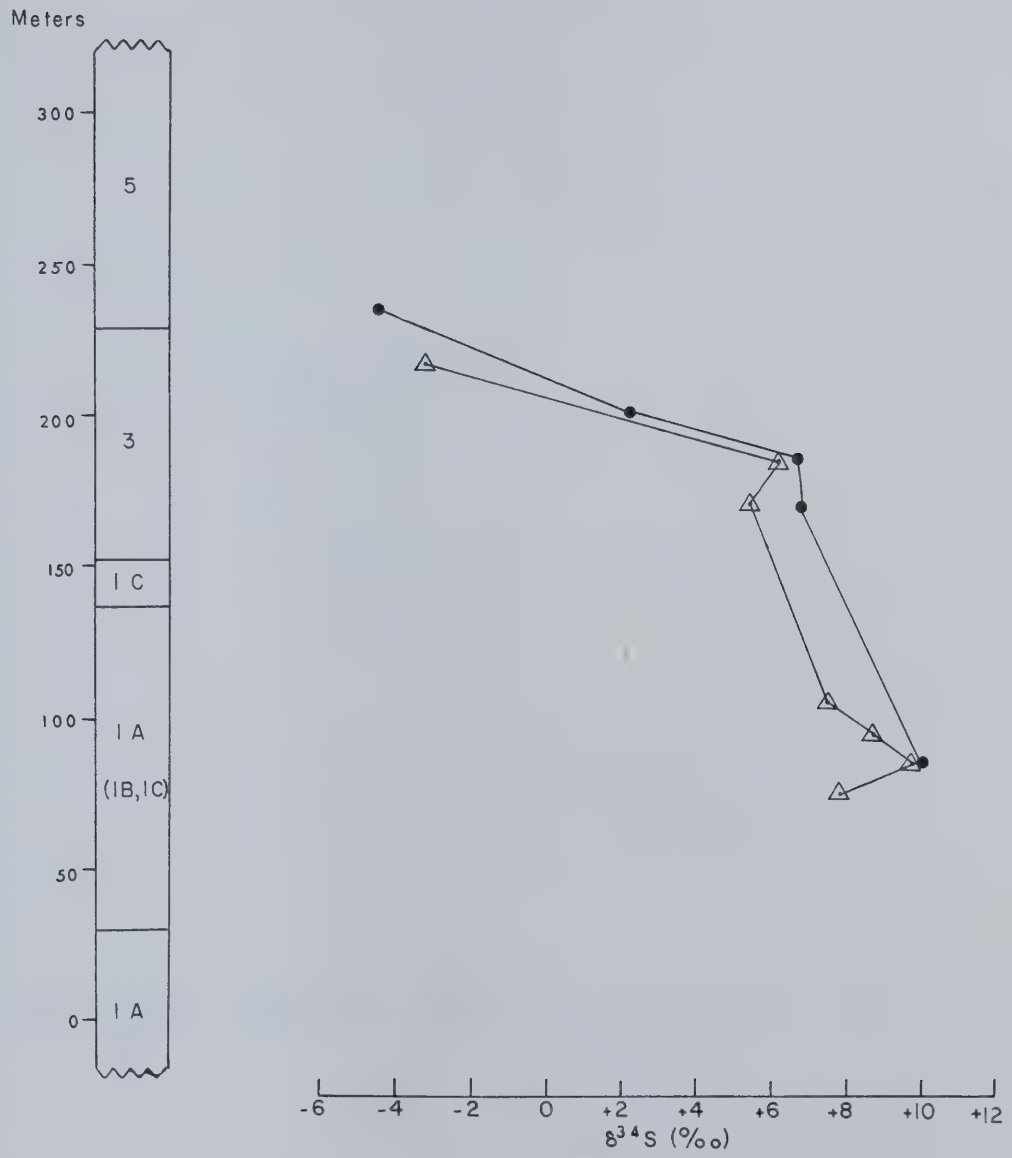



Figure 30. Sulfur isotope variations in time, space, and bedrock lithology, Hidden Creek deposit.

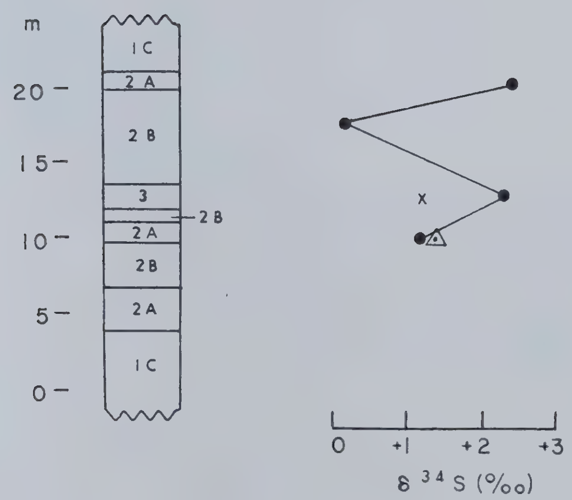



Figure 31. Sulfur isotope variations in time, space, and bedrock lithology, Bonanza deposit.

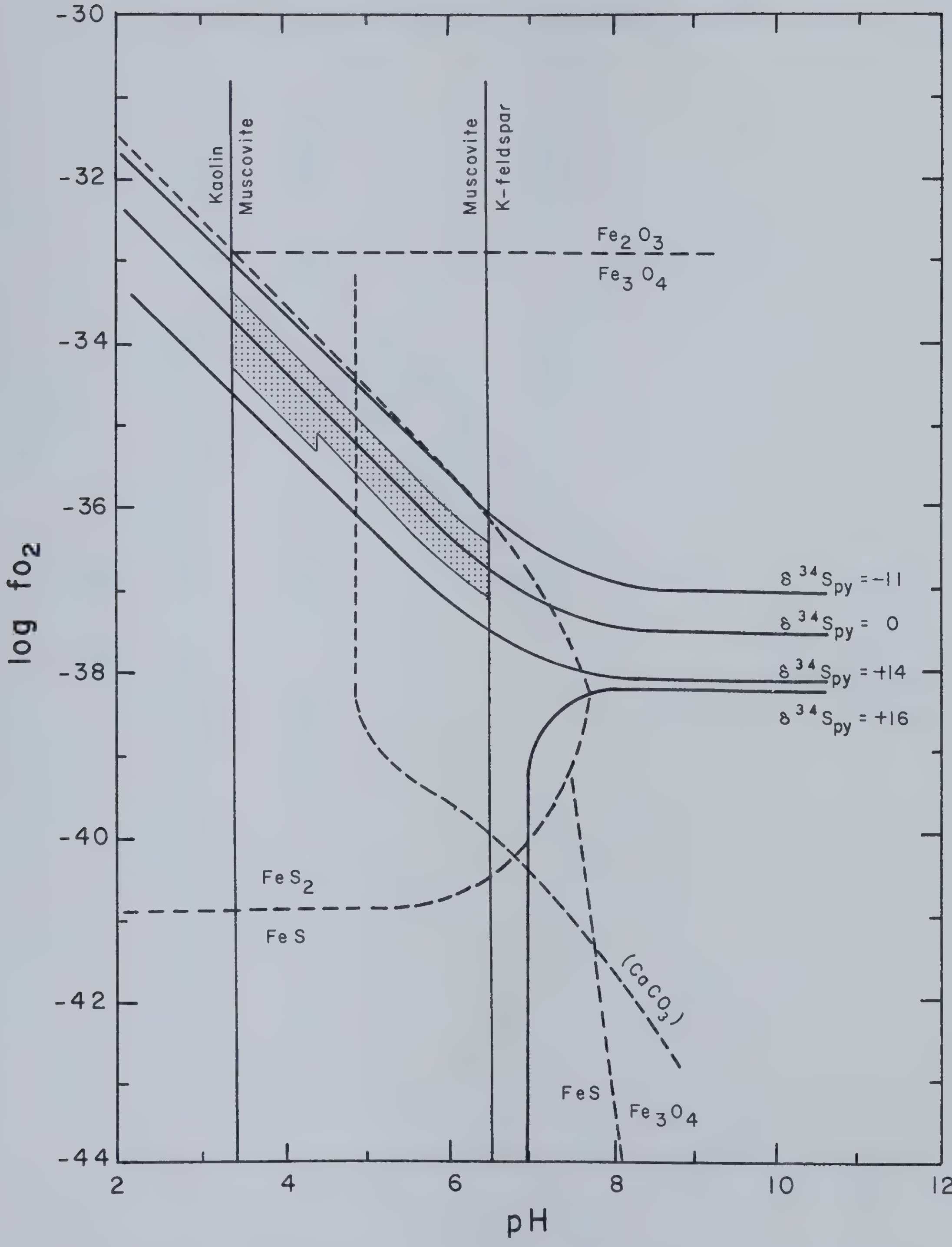



Figure 32. pH-$fO_2$ diagram for the Hidden Creek deposit. Sulfur isotope contours are drawn for $\delta^{34}S_{\Sigma S}$ = +15 per mil and T = 250°C. The Fe - S - O mineral boundaries are shown for $\Sigma S$ = 0.1 moles/kg $H_2O$. Shaded area indicates environment of ore deposition.

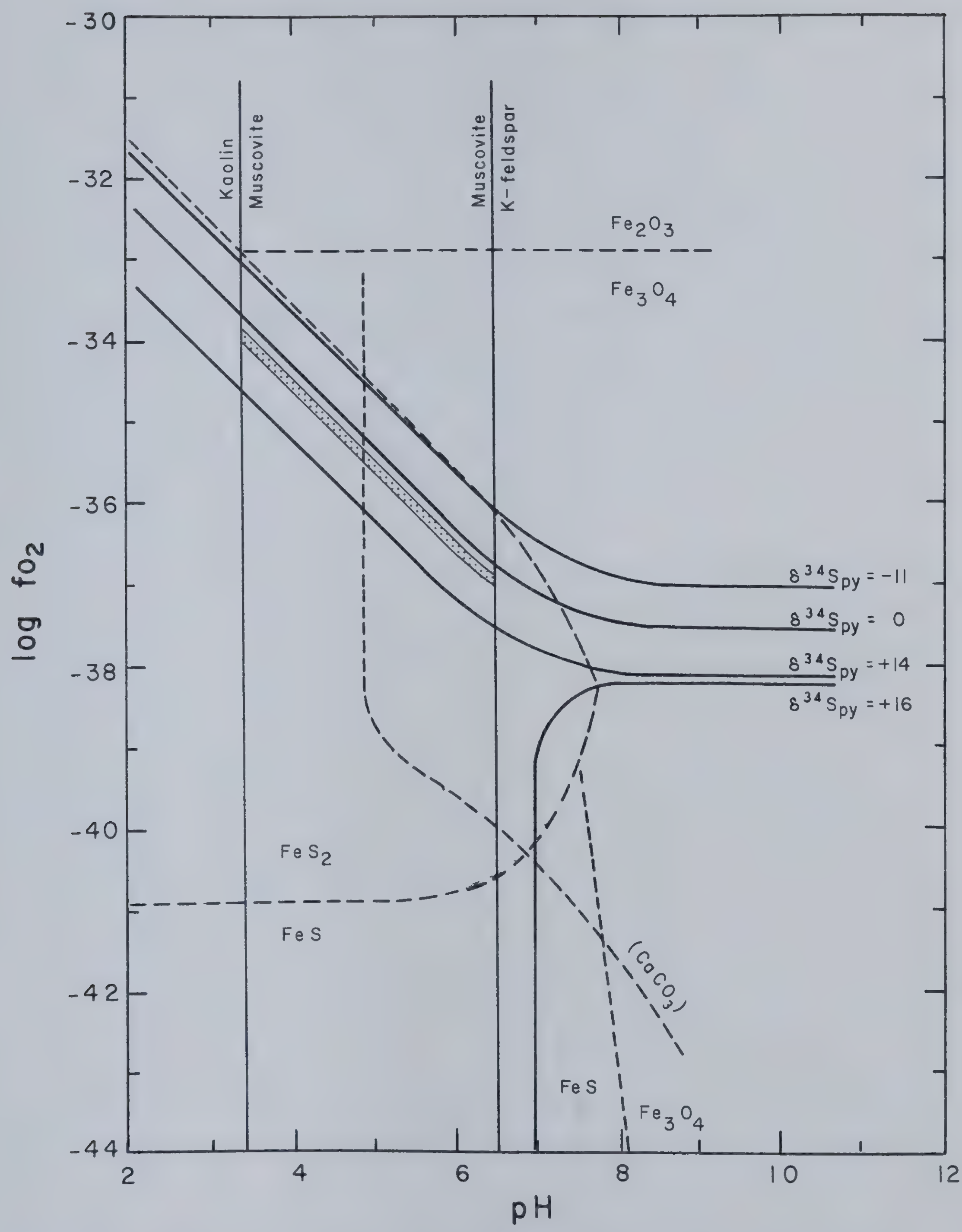



Figure 33. pH-$fO_2$ diagram for the Double Ed deposit. Sulfur isotope contours are drawn for $S^{34}S_{\Sigma S}$ = +15 per mil and T = 250°C. The Fe - S - O mineral boundaries are shown for $\Sigma S$ = 0.1 moles/kg $H_2O$. Shaded area indicates environment of ore deposition.

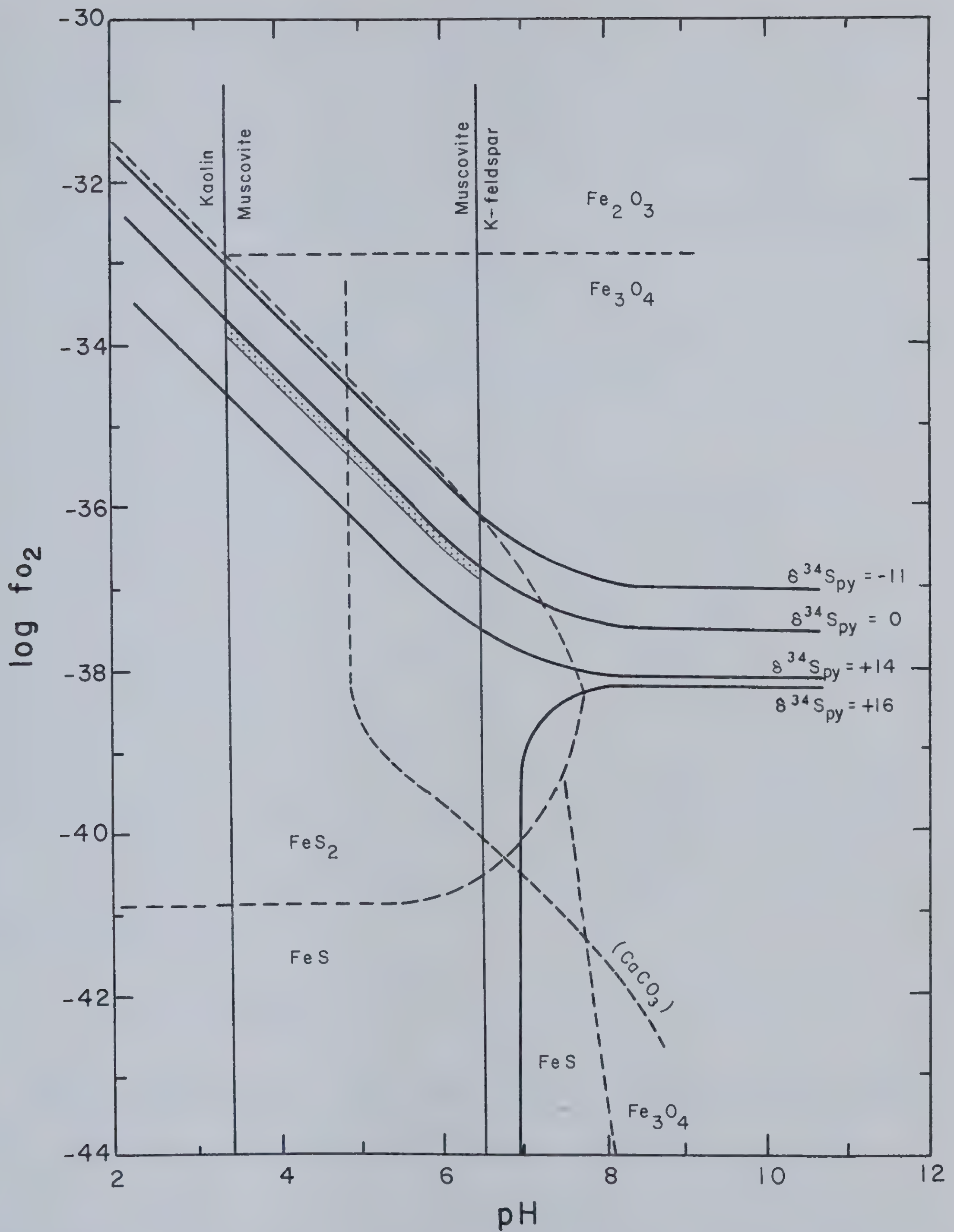



Figure 34. pH-$fO_2$ diagram for the Bonanza deposit. Sulfur isotope contours are drawn for $S^{34}S_{\Sigma S}$ = +15 per mil and T = 250°C. The Fe - S - O mineral boundaries are shown for $\Sigma S$ = 0.1 moles/kg $H_2O$. Shaded area indicates environment of ore deposition.

possible pH and oxygen fugacity ranges of the ore solutions at 250°C are shown in the shaded areas of each diagram. Ore solutions that produced the stratiform deposits had a limited range of both pH (3.0 to 6.5) and log-oxygen fugacity (-34 to -37). The mineralizing fluids at the Hidden Creek deposit had a slightly greater range than those at either the Double Ed or Bonanza, but data from all three deposits shows that similar physico-chemical conditions existed during formation of the stratiform sulfide layers.

Muscovite or sericite is found in all stratiform orebodies at Anyox; calcite is usually present. Pyrite is the most common sulfide, with pyrrhotite as the next most abundant. Some pyrrhotite is primary while some is metamorphic (especially near the portions of the sulfide zones rich in metabasaltic tuff or flows), hence is not a reliable indicator of oxygen fugacity during primary deposition. Magnetite is abundant in some sections of the massive sulfide bodies but is apparently a later alteration, probably metamorphic. Barite is absent in all deposits at Anyox.

## CONCLUSIONS

Sulfur isotopic data on the Anyox massive sulfide deposits reveals several important points about their genesis. The sulfur in the deposits was supplied by seawater sulfate from the coeval Upper Triassic sea; this means that the geothermal system at Anyox circulated significant amounts of seawater through the volcanic rock mass. The tight grouping of sulfur isotopic values indicates that isotopic equilibrium

existed between precipitating sulfide minerals and sulfur species in hydrothermal solution. If equilibrium fractionation of seawater sulfate occurred in the geothermal systems associated with each deposit, then the likelihood of bacteriological reduction of seawater sulfate to produce sulfide minerals is small. Time and space variations of sulfur isotopes at Anyox show that the Double Ed and Bonanza deposits were produced by relatively stable but small hydrothermal systems, while the Hidden Creek deposit was generated by a large and active hydrothermal system which produced fluids that evolved in time and space.

# CHAPTER VIII

## METALLOGENY AND EXPLORATION

The previous chapters have described the main geological, geochemical, and sulfur isotopic features in three massive sulfide deposits at Anyox, British Columbia. The Hidden Creek, Double Ed, and Bonanza deposits all have features which suggest an exhalative origin from a volcanogenic source. The syngenetic features are: stratiform nature of the sulfide bodies; metasedimentary rocks associated with the deposits; premetamorphic hydrothermal alteration of the volcanic rocks which underlie or form part of the sulfide-rich strata; accumulations of pyroclastic rocks (mainly metabasaltic tuff) near the sulfide deposits. Metamorphism and structural deformation have obscured many of the primary sedimentary features, but the syngenetic character of the sulfide deposits is preserved well enough to allow a reconstruction of the environment of mineralization. Other volcanogenic deposits occur in the British Columbian Cordillera but most are associated with felsic volcanism. Undoubtedly, syngenetic massive sulfide deposits in mafic metavolcanic rocks similar to the Anyox deposits occur elsewhere in the Cordillera, but either have not been recognized or have not been discovered to date. A brief review of favorable geological and geochemical criteria important for the recognition of "Anyox-type" deposits is presented as a guide to exploration of geological areas similar to Anyox.

## METALLOGENY

Two models for the genesis of the sulfide deposits at Anyox are proposed. One model, termed the "volcanic-sedimentary setting," fits the Hidden Creek deposit, while the second model, termed the "strata-bound volcanogenic sulfide deposit" fits the Double Ed and Bonanza ore bodies. The mineralizing process is similar for both model types, but differences in the length of formation time and the scale of each hydrothermal system explain the size discrepancy between the deposits. The contained copper metal in the Hidden Creek deposit is thirty-two times greater than that in either the Double Ed or Bonanza deposits. Features common to all three deposits are: average mineralogy; host rock chemistry and textures; premetamorphic hydrothermal alteration; metamorphism and structural deformation.

### Volcanic-Sedimentary Setting

The volcanic-sedimentary model for the genesis of massive sulfide deposits is well-documented and has been reviewed by a number of authors (Tatsumi, 1970; Sangster, 1972; Hutchinson, 1973; and Sawkins, 1976). The Hidden Creek orebodies are classic examples of exhalative volcanogenic massive sulfide deposits which overlie a hydrothermally altered volcanic setting containing epigenetic stockwork sulfide mineralization. The mineralization at Hidden Creek is rooted within the volcanic pile where it forms a weak dissemination around several more strongly mineralized stockwork zones. The stockwork zones extend stratigraphically upward into massive sulfide lenses enclosed either in a highly altered basaltic tuff or a siliceous metasediment (chert). The massive

sulfide lenses broaden upward and become large tabular orebodies that lie conformably upon the volcanic pile and are overlain by a thick accumulation of argillite. A model of the mineralizing mechanism that led to the development of the cupriferous sulfide deposits at Hidden Creek is proposed, based upon field relationships mapped and laboratory studies undertaken by the writer.

A thick pile of pillowed tholeiitic basalt was erupted onto the sea floor in a back-arc marine basin off the west coast of North America during the Upper Triassic period. The style of volcanism was dominated by a quiet effusion of lava onto the sea floor. Explosive volcanism was short-lived and produced only local accumulations of agglomerate and tuff. Breaks in volcanism allowed small, discontinuous layers of pelitic and fine clastic sediment to accumulate on and be incorporated in the volcanic pile. Feeder dikes and sills, which were connected to overlying vents, cut the volcanic strata in many localities. In the Hidden Creek area the terminal stages of volcanism were explosive and resulted in the buildup of pyroclastic debris, accompanied by rifting and subsidence of portions of the volcanic pile. Numerous faults cut the rift zones and related subsidence depressions, and caused brecciation of the volcanic rocks. Venting of volcanic gases and hydrothermal fluids accompanied the development of a geothermal system in the vicinity of the rift zone. Sulfide deposition in basaltic tuffs, covering the floor of the northerly trending (present position) depression, began and thin, discontinuous pods of massive sulfide formed. Pyroclastic debris, mainly tuffaceous, accumulated and was interlayered with many of the massive pyrite-pyrrhotite and chalcopyrite lenses

(composing the Number 2 and 3 deposits). After volcanism ceased, the geothermal system reached a maximum depth of 300 m and extended 1200 m laterally. A series of fumaroles over the geothermal zone discharged hot metalliferous brines which settled into nearby broad depressions on the sea floor and precipitated sulfide minerals.

Seawater sulfate supplied sulfur to the mineralizing system via chemical reduction during passage through the hot volcanic pile. Primary volcanic gases and fluids supplied some metalliferous brines and sulfur to the system, but most of the iron, copper, zinc and gold were derived from the basaltic rocks in contact with either the circulating hydrothermal fluids or the connate brines previously trapped in the underlying volcanics. The hydrothermal fluids vented onto the sea floor with only moderate force, hence did not disperse very far from the vent (geothermal alteration) zone. Silica precipitated from the exhaled fluids and formed a siliceous ooze or chert layer near the fumaroles; the silica source was the basalt, liberated during alteration of the mafic minerals. Solutions circulating back into the geothermal system were slightly enriched in silica; they silicified the weakly altered volcanic rocks of the geothermal aquifer recharge sites. The siliceous exhalative sediments accumulated in thick beds lateral to, and interlayered with, the massive sulfide bodies. Erosion of the volcanic pile and deposition of deep water pelitic sediments produced thin, discontinuous bands of epiclastic rocks, which are interbedded with the sulfide in the orebodies.

The ore solutions maintained a relatively constant pH and oxygen fugacity laterally from the vent areas. The ore solutions did evolve

in time and followed a pattern of decreasing pH and oxygen fugacity. The evolution of the ore-forming fluids is attributed to the influx of more reduced fluids into the aquifer system, possibly drawing them from the vicinity of the brine-filled depressions.

Clastic sediments encroached upon and covered the sulfide deposits with quartzo-feldspathic silt and pelitic mud. The clastic sedimentation process was slow but steady, and resulted in abundant interlayering of sulfide and barren argillite near the tops of most of the stratiform massive sulfide orebodies. The final stage of sulfide production from the hydrothermal source resulted in the formation of a few bands of massive sulfide (mostly pyrite) several meters thick, completely enclosed in the argillaceous sediments. The relatively impermeable sediments capped over the aquifer recharge areas and sealed off the supply of sea water which was essential to the geothermal (and mineralizing) system. Continued sedimentation led to the development of a thick section of argillite covering the entire volcanic pile.

## Stratabound Volcanogenic Sulfide Deposits

The second metallogenic model is applicable to the majority of the known massive sulfide deposits in the Anyox area. The Double Ed, Bonanza, Redwing, and Eden deposits are enclosed within metabasaltic lava and occur about 150 m below the main volcanic-sedimentary break in the stratigraphic column. All of the aforementioned deposits are conformably overlain and underlain by pillowed metabasalt; they also have a stratiform character indicative of formation in a sedimentary environment. The stratabound sulfide deposits have one long dimension, a restricted width, and are

generally thin; typical dimensions are 500 m long, 250 m wide, and 15 m thick.

The stratabound deposits formed during quiescent periods in the volcanic cycle; the massive sulfide orebodies contain mostly altered sedimentary rocks in their inner cores, but show an increasing volcanic component towards their upper and lower portions. At both the Double Ed and Bonanza deposits, the break in volcanism was preceded by a short period of explosive eruptions marked by the buildup of pyroclastic rocks. Small northerly (present direction) trending depressions developed on the sea floor synchronous with the explosive activity, through rifting and subsidence of the volcanic pile. Hydrothermal alteration of the basalt around portions of the rifts or depressions suggests the presence of a geothermal system. In the case of the stratabound orebodies, although the associated geothermal zones were small, seawater plus volcanic gases and fluids circulated through them and then were expelled through fumaroles on the sea floor. The hot, metal-rich brines which percolated from the vents accumulated in nearby depressions and precipitated sulfide minerals. The amount of volcanic material, mainly tuff or tuffite, in each deposit decreased with time until conditions of dominantly sedimentary deposition of sulfides, chert and pelite occurred. Massive pyrite-chalcopyrite-sphalerite layers formed in the sulfide bodies, intercalated with thin, discontinuous bands of chert or pelite.

The sulfur source in the stratabound deposits was of constant isotopic composition, which indicates a uniform source, such as seawater. The geothermal cell circulated seawater through the hot volcanic pile

and in the course of its passage, the sulfur in the fluid was reduced and made available for bonding with metallic cations in the heated solutions. The iron, copper, zinc, and gold in the sulfide deposits were derived from the volcanic fluids as well as through leaching of the altered volcanic rocks.

The temperature, pH, and oxygen fugacity of the hydrothermal brines in the mineralized depressions was nearly uniform during the formation of the massive sulfide orebodies. Sphalerite precipitated throughout the mineralizing event, but is concentrated in the non-volcanic phase of the sulfide deposits, which may reflect small oscillating shifts in the physico-chemical conditions mentioned above. Sulfide deposition occurred near the fumaroles in the small basins, therefore lateral zonation of sulfide minerals is absent; all of the stratabound sulfide orebodies fall into the proximal class of volcanogenic deposits.

A resumption of volcanic activity covered the sulfide-rich muds, in the depressions, with a blanket of basaltic tuff. The pyroclastic component in the sulfide zone increased upwards and eventually far surpassed the sulfide component. Pillowed basaltic lava flowed over the tuffaceous capping and sealed the geothermal systems off from their fluid supplies. The last volcanic episode was short-lived and a thickness of only 150 m of lava was extruded before volcanism ceased entirely.

## Origin of the Anyox Massive Sulfide Deposits

The two metallogenic models described in the preceeding section have similar host rock chemistry, hydrothermal alteration, associated pyroclastic buildups near the deposits, sulfide mineralogy, metal

sources, and sulfur sources. The main difference in the two deposit types is in the size of the orebodies and the overlying rock type.

The difference in lithology capping the deposits is a function of the time of mineralization; the stratabound orebodies formed prior to termination of effusive activity, while the stratiform deposits formed after it ceased. The volume difference between deposits is related to the size and intensity of each geothermal system which circulated hydrothermal fluids through the volcanic pile. An active geothermal zone would circulate a larger volume of fluid and vent a correspondingly greater amount of ore brines onto the sea floor; this would expand the area of sulfide precipitation and/or increase the rate of precipitation.

Similar sulfide mineralogy and contents of copper, zinc, silver, and gold suggest a common mineralizing mechanism for all the Anyox deposits in spite of differences in geological setting. A copper enrichment occurs in the alteration zones associated with each orebody; this enrichment is significantly greater than the background copper content of basalt in the area and points to a net introduction of copper from outside the alteration zone. Zinc, gold, and silver enrichments are also associated with the high copper values. The source of the metallic elements in the deposits is either from alteration of the basalt in the geothermal zones, or magmatic gases and fluids, or from expulsion of connate waters trapped between pillows and in tuff beds in the underlying volcanic pile. The sulfur source was sea water sulfate with some possible contribution from primary volcanic fluids.

The model of ore genesis at Anyox calls for the establishment of a geothermal system (heat cell) in a basaltic rock mass near an area of

rifting and subsidence (Solomon, 1976). Metalliferous brines circulating in the geothermal system are slowly vented onto the sea floor, and accumulate in depressions nearby. Physico-chemical conditions allow precipitation of sulfide minerals both in the alteration zone and on the sea floor. A time break, long enough to allow for undiluted sulfide layers to accumulate, is essential to the mineralizing process. A protective capping on each deposit is necessary to preserve it from erosion.

### Tectonic Setting of Ore Deposition

Preliminary trace element geochemistry indicates that the volcanogenic massive sulfide deposits at Anyox formed in a back-arc setting on the ocean floor near a plate margin. A modern-day equivalent of such a setting would be the Marianas basin which underlies the Phillippine Sea. At Anyox, the absence of ultramafic rocks and the presence of a thick assemblage of fine-grained geosynclinal metasedimentary rocks indicates that the volcanic pile formed near a destructive plate margin in an active orogenic zone. The original size of the back-arc ocean basin is unknown because of a lack of information about regional correlation of stratigraphic assemblages, as well as complications induced by large-scale tectonic displacements and intrusion of the Coast Plutonic Complex. Based upon the lithologies present and the stratigraphic column, the metamorphosed volcanic-sedimentary assemblage at Anyox is correlated with the Karmutsen, Kunga, and Maude formations. To date, no occurrences of the Karmutsen formation have been recognized on the mainland northeast of the Queen Charlotte Islands (H. W. Tipper, D. W. Campbell, personal

communication). Both Dr. Tipper and Dr. Campbell agree that Anyox may be part of the Karmutsen formation that has undergone tectonic transport as a large fault block, and has moved a considerable distance northeast of its original site of formation. Dr. Tipper notes that major faults are known in the area, and one such fault may separate the Hazelton Group at Alice Arm from the Bowser Group directly to the east.

A detailed account of the regional tectonism of British Columbia is beyond the scope of this thesis. It is clear that the post-depositional tectonic history of the Anyox area is complex and has been influenced by regional tectonism. The remains of the Upper Triassic-Lower Jurassic ocean basin in which the Anyox deposits formed, have been disrupted by regional transcurrent block faulting and intrusion of the Coast Plutonic Complex. Any regional correlation of Triassic or Jurassic stratigraphy near Anyox should be done with this information in mind. The most important point is that the rock mass which contains the Anyox massive sulfide deposits may have undergone significant tectonic transport from its original site of formation; the assumption that a back-arc basin existed during Triassic-Jurassic time at Anyox's present position may be erroneous.

## Comparative Volcanogenic Deposits

Cupriferous massive sulfide deposits associated with basaltic or metabasaltic host rocks exist in numerous localities around the world. Examples of such deposits are found at Anyox, British Columbia; Notre Dame Bay, Newfoundland; Løkken, Norway; Troodoos, Cyprus; and Besshi,

Japan. The Notre Dame Bay and Cyprus deposits both have ultramafic rocks associated with them, unlike the deposits at Anyox, Løkken, or Besshi. In the deposits of the Besshi district in Japan, the stratiform massive sulfide occurs in metabasalt and in metapelitic zones, but no recognizable fumarole or hydrothermal vent zones are associated with the sulfide mineralization (Banno, Takeda and Sato, 1970; Kanehira and Tatsumi, 1970). The Løkken deposit has a hydrothermal vent system that underlies the massive sulfide deposit, which is stratabound in a series of metabasaltic pillowed lava flows (Vokes and Gale, 1976). At Anyox, the Bonanza and Double Ed deposits are geologically similar to the Løkken and Besshi deposits.

The term "Besshi-type" deposit has been applied to the cupriferous iron sulfide deposits associated with mafic volcanic rocks, chert, and geosynclinal greywackes (Sawkins, 1976). The deposits at Anyox fit only loosely into the above classification, for the following reasons: a much larger volume of mafic metavolcanic rocks occurs at Anyox than at Besshi; alteration zones occur with each deposit at Anyox; the Hidden Creek massive sulfide bodies are more tabular than the narrow lenticular Besshi orebodies.

In British Columbia, the only other known example of a Besshi-type deposit is the Goldstream massive sulfide copper-zinc orebody near Revelstoke. At the Goldstream deposit, a thin band, over 1 km long, of stratiform massive sulfide occurs in metapelites with metabasaltic rocks nearby (T. Höy, 1979). Numerous volcanogenic massive sulfide deposits exist throughout the British Columbia Cordillera, but are dominantly associated with intermediate to felsic volcanic rocks, hence

are not Besshi-type deposits. Figure 9 (in pocket) shows the distribution of the volcanogenic massive sulfide deposits in British Columbia.

## EXPLORATION PARAMETERS

Massive sulfide deposits similar to the Hidden Creek orebodies make attractive exploration targets because they are spatially confined and carry a high amount of economic elements per ton of rock excavated by mining. The most valuable part of the Hidden Creek deposit was a seven million tonne section of ore with an average grade of 3.3% copper. A number of exploration guidelines have been formulated to aid in future work which may be undertaken at Anyox or in similar geological terrains. These guidelines reflect the experience gained in the Anyox camp and are meant to be applied to the search for an "Anyox-type" of deposit elsewhere in the Cordillera.

### Geological Mapping

Geological mapping can be a powerful and cost-effective exploration tool and should be emphasized in both reconnaissance and property exploration programs. The main uses of geological mapping are:

(a) definition of the stratigraphic and structural trends of volcanic lithologies;

(b) recognition of pyroclastic buildups in the volcanic pile;

(c) recognition and delineation of premetamorphic hydrothermal alteration within the volcanic strata;

(d) separation of subaerial and submarine volcanic piles;

(e) locate economic sulfide mineralization in outcrop or in glacial float.

All of the above points must be dealt with at some point in an exploration program because they have an important bearing on geochemical and geophysical trends. Anomalies in altered submarine basalt near a volcanic-sedimentary break and accompanied by pyroclastic buildups are higher priority drill targets than anomalies in unaltered subaerial basalt flows. Knowledge of the regional geology is important in the logging and interpretation of diamond drill core, especially in areas covered with overburden, where little outcrop is present.

### Geochemistry

A variety of geochemical methods may be applied to mineral exploration where specific problems need to be solved. Major element chemistry of the basalt will not answer the problems of metal dispersion at the volcanic-sedimentary interface. At Anyox, the study of the major and trace element distributions solved some important questions concerning ore genesis and were found to be reliable indicators of mineralization.

There are two useful applications that major element geochemistry may have in a prospecting program. The first is the recognition of metabasaltic terrain that may host copper-rich volcanogenic massive sulfide deposits. Numerous roof pendants occur in the coast crystalline belt and may be similar to Anyox in terms of tectonic setting during volcanism. If a pendant contains a significant section of undifferentiated tholeiitic pillow basalt overlain by pelitic sedimentary rocks, then the area has the potential to host a massive sulfide deposit similar to those studied at Anyox. When defining potentially favorable basaltic

terrains, only a limited number of whole rock major element analyses need be taken to assess if follow-up work is warranted.

The second application is where either mineralization or an alteration zone exists in the volcanic rocks. This case is of a specific nature and major element geochemistry can provide important data on spacial trends of alteration intensity, which may indicate paths followed by ore solutions and lead to the development of a metallogenic model for the local system. Such modelling can play an important role in advanced geophysical and diamond drill exploration of a prospect, especially in the case of blind deposits.

The extensive use of whole rock major element geochemistry is unnecessary in a routine prospecting program carried out in an undifferentiated tholeiitic basalt terrain. Alteration zones are marked by enrichments in quartz, chlorite, iron sulfides, magnetite, albite and sericite, which are visible in outcrop or in thin section. Albitized rocks are often too fine-grained to diagnose megascopically, but are easily recognizable in thin section. Major element geochemistry adds little to the information available from field mapping and optical mineralogy, hence should be applied to specific problems where rock chemistry is most useful (such as the two applications suggested above).

Trace element geochemistry of bedrock samples is useful in two cases. One case is in measuring copper concentration of metabasaltic (altered or unaltered) rocks; the second case is in measuring copper, zinc and sulfur contents of the cherty sedimentary rocks (quartzite) along the volcanic-sedimentary contact. Both cases of trace element geochemistry can be applied to the search for "blind" massive sulfide

deposits. Research at Anyox showed that anomalous copper concentrations occur in hydrothermally altered basaltic rocks which either underlie or are lateral to the known massive sulfide deposits. Copper anomalies in altered basalt occurred in unmineralized areas at Anyox as well, and point out that copper anomalies are associated with massive sulfide deposits, although the reverse is not always the case.

Analyses of rock samples taken along the volcanic-sedimentary contact is not as good a prospecting method as sampling the copper contents of the basalt. Metal dispersion away from mineralized areas appears spacially restricted at Anyox, therefore the small zones of metal enrichment make poor prospecting targets and may be so subtle that they are overlooked. The small dispersions of metals away from the Hidden Creek deposit may reflect the seawater-mixing history and the type of hydrothermal brine plume which vented onto the sea floor. A plume that separated into two phases, one on the sea floor and the other spreading out some distance above it, would produce a large metal dispersion away from the vent area (Solomon and Walshe, 1979).

In the wet, rugged, and often overburden-covered terrain of the Coast Range Mountains, soil sampling should prove to be an effective exploration method. Soil sampling was not employed at Anyox due to widespread contamination of the soil with dust and gas from the mining and smelting operations. Stream silt geochemistry delineated positive geochemical anomalies in the area and appears to be a reliable indication of copper mineralization.

Other geochemical exploration techniques that may be used are heavy mineral geochemistry or sulfur isotopes. Heavy minerals such as

pyrite and chalcopyrite may be more diagnostic of mineralization than ordinary silt samples are, because the diluting effect of the silicate gangue minerals is removed. This method was tested at Anyox, but was not as effective as hoped, mainly because of the high stream gradients in the area which wash most of the silt away (2 kg are needed for one sample). Sulfur isotopes may provide information on the genesis of the sulfide minerals analyzed, but are too costly and time-consuming to run routinely during an exploration program.

### Geophysics

Several modern geophysical exploration techniques were used during the ore search at Anyox. Cominco Limited has tested electro-magnetic and magnetic methods and found that both techniques respond to the massive sulfide deposits in the area. Two factors limit the effectiveness of the geophysical methods: one is the presence of carbonaceous material near the volcanic-sedimentary contact, which produces strong electro-magnetic conductors; the second is a poor magnetic contrast between the metabasalt and overlying metasedimentary rocks, often making it difficult to distinguish the two lithologies in overburden-covered areas. Aero-magnetic surveys conducted by the federal government show a positive response over the Hidden Creek deposit, attributed to the pyrrhotite and magnetite associated with the massive sulfide zones. A low level airborne magnetometer survey may be an effective "first pass" exploration technique in areas similar to Anyox. To the writer's knowledge, other geophysical techniques have not been tested at Anyox.

### Diamond Drill Exploration

In the search for a massive sulfide body at Anyox, one may encounter anything from a restricted zone of disseminated chalcopyrite to a large tabular body of massive pyrite, pyrrhotite and chalcopyrite. The size and shape of the target varies from long and narrow (150 m by 400 m) to large tabular bodies (600 m by 400 m) with high grade copper-zinc lenses. A diamond drill hole must come to within 600 to 400 m of the center of an isolated tabular deposit to intersect mineralization, but may encounter signs of mineralization up to 800 m from the deposit center. At Anyox, diamond drilling for blind deposits is both expensive and difficult. Drill hole lengths exceeding 300 m are common and severe deflection of the hole is often encountered while coring through the structurally deformed metasedimentary rocks. In most places at Anyox, deep diamond drilling is necessary for further exploration. Unfortunately, even if an orebody is outlined at depth, the development cost of sinking a 300 m shaft may be so high that the operation generates only marginal profits. Such factors are the greatest drawback to future exploration in the area and unless the long-term price of copper increases dramatically, the massive sulfide deposits at Anyox will remain unexploited.

# CHAPTER IX

# CONCLUSION

This thesis attempts to establish the volcanogenic nature of the cupriferous massive sulfide deposits at Anyox, British Columbia. The thesis is supported by previously gathered information and the writer's mapping, research data and observations. Detailed geological maps and stratigraphic columns were drawn for each of the three deposits and clearly show the conformable nature of the massive sulfide bodies. Premetamorphic hydrothermal alteration was mapped around each deposit and was defined mineralogically and geochemically. The mineralogy of the sulfide-rich strata was studied in polished sections and found to be similar for each orebody; the deposits have a simple sulfide mineralogy which consists of mostly pyrite and pyrrhotite with subordinate chalcopyrite and sphalerite.

Major element geochemistry of the unaltered (but metamorphosed) basalt show the pillow lavas to have originally been tholeiitic basalt. Additional major element analyses of altered basalt allowed a calculation of the gains and losses of important cations from the altered rock mass. Alteration of the basalt resulted in gains of iron, sulfur, and magnesium, and losses in calcium, sodium, and silica in the altered rocks. Trace element analyses were done to study copper zonation and metal dispersion patterns around the deposits. Copper was strongly enriched in the alteration zones and within the massive

sulfide layers. Metal dispersion in meta-exhalative siliceous sinters along the volcanic-sedimentary contact at Hidden Creek mine is poorly developed and indicative of a relatively slow percolation of hydrothermal fluids onto the sea floor. Other trace element analyses, of yttrium, niobium, chromium and zirconium, were plotted on discrimination diagrams, and suggest that the basalt at Anyox was erupted in a back-arc ocean basin near a plate margin, similar to that of the Løkken deposit in Norway.

Sulfur isotopes were analyzed to provide data on the genesis of the sulfide minerals. Pyrite-chalcopyrite and pyrite-sphalerite pairs yielded temperatures of upper greenschist grades of metamorphism; they did not yield temperatures of formation of the primary sulfides precipitated on the sea floor. Overall sulfur isotope distributions in the sulfide minerals from the deposits are preserved and are comparable to data from similar deposits around the world.

Based upon the information presently available, the writer outlined metallogenic models applicable to the stratabound and stratiform types of orebodies. Two general classes of volcanogenic cupriferous massive sulfide deposits have been recognized at Anyox. One class is completely enclosed or hosted in metabasaltic lava flows and tuffs (the Double Ed, Bonanza, and Hidden Creek Stockwork and Numbers 2 and 3 deposits); the other class occurs at the volcanic-sedimentary contact and is characterized by a large alteration zone in the metabasalt which underlies the massive sulfide mineralization (the Hidden Creek 1, 4, 5, 6, 7, and 8 deposits). The mineralizing mechanism is

identical in both classes of deposits; metal-rich brines were derived from volcanic fluids or gases, and sulfur was obtained from the reduction of seawater sulfate. The metal-rich brines bonded with the aqueous reduced sulfur species and precipitated in environments of favorable physico-chemical conditions either in the altered basaltic pile or on the sea floor in depressions near the hot springs.

The massive sulfide deposits at Anyox were formed in a deep ocean basin near a plate boundary. The rocks are correlated with the Karmutsen formation of Upper Triassic age; there is evidence that block faulting and tectonic transport may have moved the Anyox area "en mass" substantially north of its original site of formation. The Anyox orebodies are classified as "Besshi-type" deposits and are similar to the massive sulfide bodies found in the Besshi area of Japan and the Løkken area of Norway. The only other known Besshi-type deposits in British Columbia are in the Goldstream locality, north of Revelstoke.

The search for new deposits in the Anyox area or in similar geological terrain should place heavy emphasis on geological mapping. The best indications of areas favorable for the development of Besshi-type massive sulfide deposits are: submarine mafic volcanic rocks; premetamorphic hydrothermal alteration; and pyroclastic buildups in the volcanic stratigraphy. Bedrock geochemistry is useful in detecting anomalous copper concentrations in volcanic or metavolcanic rocks and is a significant indicator of mineralization when it occurs in hydrothermally altered metavolcanic rocks. Copper or zinc anomalies along the volcanic-sedimentary contact are a

favorable indicator of mineralization down-dip or along strike.

The writer concludes that the Hidden Creek, Double Ed, and Bonanza copper deposits originally accumulated as metalliferous muds and precipitates in hot brine-filled depressions on the sea floor. The brine pools were fed by hydrothermal fluids expelled from active geothermal systems which circulated coeval seawater and connate brines within a recently erupted basaltic volcanic pile during the Mesozoic era.

# BIBLIOGRAPHY


Bachinski, D. J., 1977, Sulfur isotopic composition of ophiolitic cupriferous iron sulfide deposits, Notre Dame Bay, Newfoundland: Econ. Geol., v. 72, p. 243-257.

---- 1977, Alteration associated with metamorphosed ophiolitic cupriferous iron sulfide deposits; Whalesback Mine, Notre Dame Bay, Newfoundland: Mineralium Deposita, v. 12, p. 48-63.

---- 1978, Sulfur isotopic composition of thermally metamorphosed cupriferous iron sulfide ores associated with cordierite-anthophyllite rocks, Gull Pond, Newfoundland: Econ. Geol., v. 73, p. 64-72.

Bancroft, J. A., 1918, Preliminary report on the geology of the Anyox-map area, which includes the Hidden Creek and Bonanza copper deposits: Granby Consolidated Mining, Smelting and Power Company Limited, unpublished report.

Banno, S., Takeda, H., Sato, H., 1970, Geology and ore deposits in the Besshi mining district: IMA-IAGOD Guidebook 9, Excursion B5, Japan 1970, Society of Mining Geologists of Japan.

Barnes, H. L., 1967, ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, Inc., 670 p.

Barth, T. F. W., 1948, Oxygen in rocks: a basis for petrographic calculations: Jour. of Geol., v. 56, p. 50-60.

Berry, L. G., and Mason, B., 1959, Mineralogy: concepts, descriptions, determinations: San Francisco, W. H. Freeman and Co., 630 p.

Billings, M. P., 1972, Structural geology: New Jersey, Prentice-Hall, Inc., 606 p.

Blackadar, R. G., Dumych, H., and Griffin, P. J., 1975, Guide to authors - a guide for the preparation of geological maps and reports: Canada Geol. Surv. Miscellaneous Report 16, 199 p.

Bonatti, E., Guerstein-Honnorex, B., Honnorez, J., 1976, Copper-iron sulfide mineralizations from the equatorial Mid-Atlantic Ridge: Econ. Geol., v. 71, p. 1515-1525.

British Columbia Ministry of Energy, Mines and Petroleum Resources, "Minfile", Statistics, 1979, A computerized inventory of mineral occurrences maintained by the British Columbia Ministry of Energy, Mines and Petroleum Resources: Victoria, B. C. Ministry of Energy, Mines and Petroleum Resources.

Campbell, D. W., 1979, Personal communication.

Campbell, F. A., Ethier, V. G., Krouse, H. R., Both, R. A., 1978, Isotopic composition of sulfur in the Sullivan Orebody, British Columbia: Econ. Geol., v. 73, p. 246-268.

Carmichael, I. S. E., Turner, F. J., Verhoogen, J., 1974, Igneous petrology: New York, McGraw-Hill Book Co., 739 p.

Carter, N. C., and Grove, E. W., 1972, Geological compilation map of the Stewart, Anyox, Alice Arm, and Terrace areas: British Columbia Ministry of Energy, Mines and Pet. Res., Preliminary Map No. 8.

Coleman, M. L., 1977, Sulfur isotopes in petrology: Jour. Geol. Soc. Lond., v. 133, p. 593-608.

Deer, W. A., Howie, R. A., Zussman, J., 1966, An introduction to the rock forming minerals: London, Longman Group Limited, 528 p.

Degens, E. T., and Ross, D. A., 1969, eds., Hot brines and recent heavy metal deposits in the Red Sea: New York, Springer-Verlag, 600 p.

Dolmage, V., 1922, Coast and islands of British Columbia between Douglas Channel and the Alaskan Boundary: Geol. Surv., Can., Sum. Rept., 1922, Part A, p. 9-34.

Edwards, A. B., 1960, Textures of ore minerals and their significance: Melbourne, The Australasian Institute of Mining and Metallurgy, 242 p.

Elliott, R. L., Smith, J. G., Hudson, T., 1976, Upper high level plutons of the Smeaton Bay area, Southeastern Alaska: U. S. Geol. Survey Open-File Report No. 76-507, 15 p.

Ethier, V. G., Campbell, F. A., Both, R. A., and Krouse, H. R., 1976, Geolgocial setting of the Sullivan orebody and estimates of temperatures and pressure of metamorphism: Econ. Geol., v. 71, p. 1570-1588.

Floyd, P. A., and Winchester, J. A., 1975, Magma type and tectonic setting discrimination using immobile elements: Earth Planet. Sci. Letters, v. 27, p. 211-218.

Francheteau, J., Needham, H. D., Choukroune, P., Juteau, T., Seguret, M., Ballard, R. D., Fox, P. J., Normark, W., Carranza, A., Cordoba, D., Guerrero, J., Rangin, C., Bougault, H., Cambon, P., Hekinian, R., 1979, Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise: Nature, v. 277, p. 523-528.

Freeze, E., 1951, Regional geologic map of the Anyox area, British Columbia: Cominco Ltd., unpublished map.

Garrison, R. E., 1974, Radiolarian cherts, pelagic limestones, and igneous rocks in eugeosynclinal assemblages in Hsu, K. J., and Jenkyns, H. C., eds., Pelagic Sediments: On Land and Under the Sea: Oxford, Blackwell Scientific Publications, p. 367-399.

Garson, M. S., and Mitchell, A. H. G., 1977, Mineralization at destructive plate boundaries: a brief review, in Volcanic processes in ore genesis: Geol. Soc. of London, Spec. Pub. No. 7, p. 81-97.

Gilbert, G., 1939, Granby Property (Hidden Creek Mine): Cominco Limited, unpublished report.

Gill, F. D., 1960, Geological plan of the Double Ed deposit, 500 foot level: Cominco Limited, unpublished map.

Graf, J. L., Jr., 1977, Rare earth elements as hydrothermal tracers during the formation of massive sulfide deposits in volcanic rocks: Econ. Geol., v. 72, p. 527-548.

Griffiths, J. R., 1977, Mesozoic-early Cenozoic volcanism, plutonism, and mineralization in southern British Columbia: A plate tectonic synthesis: Canadian Jour. Earth Sci., v. 14, p. 1611-1624.

Grove, E. W., 1965, Observatory Inlet, Granby Bay area, in British Columbia Ministry of Energy, Mines and Pet. Res., Annual Report, p. 57-59.

---- 1971, Geology and mineral deposits of the Stewart area, northwestern British Columbia: British Columbia Ministry of Energy, Mines and Pet. Res., Bull. 58, 219 p.

Hanson, G., 1921, Upper Kitsault Valley, British Columbia: Canada Geol. Surv., Sum. Rept., pt. A, p. 7-21.

---- 1935, Portland Canal Area, British Columbia: Canada Geol. Surv., Mem. 175, 165 p.

Harris, J., 1977, Major element analytical techniques, Cominco research laboratory, Vancouver, British Columbia: personal communication.

Heddle, D. W., 1953, Geological report on the Double Ed Property: Cominco Limited, unpublished report.

---- 1954, Geological report on the Double Ed Property: Cominco Limited, unpublished report.

---- 1961, Geological report on the Double Ed Property: Cominco Limited, unpublished report.

---- 1964, Geological report on the Anyox 1961 and 1963 drill programs: Cominco Limited, unpublished report.

---- 1968, Leaching and further exploration possibilities at Anyox: Cominco Limited, unpublished report.

Heinrich, E. Wm., 1965, Microscopic identification of minerals: New York, McGraw-Hill Book Co., 414 p.

Holmes, R., and Tooms, J. S., 1972, Dispersion from a submarine exhalative orebody, in Jones, M. J., ed., Geochemical Exploration 1972: London, Inst. Mining and Metallurgy, p. 193-202.

Honnorez, J., Honnorez-Guerstein, B., Valette, J., Wauschkuhn, A., Present day formation of an exhalative sulfide deposit at Vulcano (Tyrrhenian Sea), Part II: Active crystallization of fumarolic sulfides in the volcanic sediments of the Baia di Levante, in Amstutz, G. C., and Bernard, A. J., eds., Ores in sediments: New York, Springer-Verlag, p. 139-166.

Höy, T., 1979, Geology of the Goldstream area: British Columbia Ministry of Energy, Mines and Pet. Res., Bull. 71, 50 p.

Hutchinson, R. W., 1973, Volcanogenic sulfide deposits and their metallogenic significance: Econ. Geol., v. 68, p. 1223-1246.

Hutchison, C. S., 1974, Laboratory handbook of petrographic techniques: New York, John Wiley and Sons, 527 p.

Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Jour. Earth Sci., v. 8, p. 523-548.

Jensen, M. L., 1967, Sulfur isotopes and mineral genesis, Chap. 5, in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, Inc., p. 143-165.

---- and Nakai, N., 1963, Sulfur isotope meteorite standards: results and recommendations, in Biochemistry of Sulfur Isotopes: Proc. Nat. Sci. Found. Symp., Yale Univ., April, 1962, p. 1-15.

Jeletzky, J. A., 1970, Some salient features of early Mesozoic history of insular tectonic belt, western British Columbia: Canada Geol. Surv. Paper 69-14, 26 p.

Kajiwara, Y., 1973, Significance of cyclic seawater as a possible determinant of rock alteration facies in the earth's crust: Geochem. Jour., v. 7, p. 23-36.

---- and Date, J., 1971, Sulfur isotope study of Kuroko-type and Kieslager-type stratabound massive sulfide deposits in Japan: Geochem. Jour., v. 5, p. 133-150.

---- and Krouse, H. R., 1971, Sulfur isotope partitioning in metallic sulfide systems: Canadian Jour. Earth Sci., v. 8, p. 1397-1408.

Kajiwara, Y., Krouse, H. R., and Sasaki, A., 1969, Experimental study of sulfur isotope fractionation between co-existing sulfide minerals: Earth Planet. Sci. Letters, v. 7, p. 271-277.

Kanehira, K., and Tatsumi, T., 1970, Bedded cupriferous iron sulphide deposits in Japan, in Tatsumi, T., ed., Volcanism and ore genesis: Tokyo, Univ. of Tokyo Press, p. 51-76.

Kerr, P. F., 1959, Optical Mineralogy, (third edition): New York, McGraw-Hill Book Co., 442 p.

Krouse, H. R., 1978, Mass spectrometric results for the Anyox $SO_2$ gas samples: Written communication.

---- 1978, Mass spectrometric equipment and analytical procedures used for sulfur isotopes in the Department of Physics, University of Calgary: Personal communication.

Kuo, S. L., 1976, Geology and geochemistry of stratabound ore deposits in south-central Yukon Territory and southwestern District of Mackenzie, Northwest Territories: Unpub. PhD thesis, University of Alberta, Edmonton.

---- 1977, Procedures for the direct oxidation of sulfides to produce $SO_2$ gas for sulfur isotope mass spectrometry: Personal communication.

Lambert, I. B., and Sato, T., 1974, The Kuroko and associated ore deposits of Japan: A review of their features and metallogenesis: Econ. Geol., v. 69, p. 1215-1236.

Large, R. R., 1977, Chemical evolution and zonation of massive sulfide deposits in volcanic terrains: Econ. Geol., v. 72, p. 549-572.

Macnamara, J., and Thode, H. G., 1950, Comparison of the isotopic constitution of terrestrial and meteoritic sulphur: Phys. Rev., v. 78, p. 307.

McArthur, D. R. B., 1978, How to write SI: Metric Commission Canada, Ministry of Supply and Services Canada, Catalog No. Me31-3/1978, 8 p.

McBirney, A. R., 1971, Oceanic volcanism: a review: Reviews of Geophysics and Space Physics, v. 9, p. 523 - 556.

McConnell, R. G., 1912, Portions of Portland Canal and Skeena Mining Divisions, Skeena District, British Columbia: Canada Geol. Surv. Mem. 32, p. 73-95.

Miyashiro, A., 1973, Metamorphism and metamorphic belts: London, George Allen and Unwin Ltd., 492 p.

Mizutani, Y., and Shinya, O., 1973, Separation of $CO_2$ from $SO_2$ with frozen n-pentane as a technique for the precision analysis of $^{18}O$ in sulfates: Mass Spectroscopy, v. 21, p. 255-258.

Moorhouse, W. W., 1959, The study of rocks in thin section: New York, Harper and Row, Publishers, 514 p.

Monger, J. W. H., 1977, Ophiolitic assemblages in the Canadian Cordillera, in Coleman, R. G., and Irwin, W. P., eds., North American Ophiolites: State of Oregon, Department of Geology and Mineral Industries, Bull. 95, 183 p.

Monger, J. W. H., and Price, R. A., 1979, Geodynamic evolution of the Canadian Cordillera - progress and problems: Canadian Jour. Earth Sci., v. 7, p. 770-791.

Nelson, N. E., 1935, The Hidden Creek ore-bodies: Canadian Inst. Mining and Metallurgy, v. 38, p. 349-357.

---- 1936, The Bonanza Mine: Cominco Limited, unpublished report.

Ohmoto, H., 1972, Systematics of sulfur and carbon isotopes in hydrothermal ore deposits: Econ. Geol., v. 67, p. 551-578.

Ollier, C., Volcanoes: Cambridge, The MIT Press, 177 p.

Osatenko, M. J., 1976, Geological and geochemical report on the AHW, SUNDOG FR., SUNRISE and RUBY FR. mineral claims in the Anyox area: British Columbia Ministry of Energy, Mines and Petroleum Resources, Assessment Report 6137.

Parasins, D. S., 1972, Principles of applied geophysics: London, Chapman and Hall Ltd., 214 p.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analysis: Earth Planet. Sci. Letters., v. 19, p. 290-300.

Pearce, J. A., and Gale, G. H., 1977, Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks: Geol. Soc. of London, Spec. Pub. No. 7, p. 14-24.

Plimer, I. R., and Finlow-Bates, T., 1978, Relationship between the primary iron sulphide species, sulphur source, depth of formation and age of submarine exhalative sulphide deposits: Mineralium Deposita, v. 13, p. 399-410.

Prinz, M., 1968, Geochemistry of basaltic rocks: trace elements, in Hess, H., and Polderaart, A., eds., Basalts: New York, Interscience Publishers, p. 271-323.

Ribbe, P. H., 1974, ed., Sulfide mineralogy: Mineralogical Society of America, Short Course Notes, v. 1, 281 p.

Rona, P. A., 1978, Criteria for recognition of hydrothermal mineral deposits in oceanic crust: Econ. Geol., v. 73, p. 135-160.

Rösler, H. J., and Lange, H., 1972, Geochemical tables: Amsterdam, Elsevier Publishing Company, 468 p.

Rye, R. O., and Czamanske, G. K., 1969, Experimental determination of sphalerite-galena sulfur isotope fractionation and application to the ores at Providencia, Mexico: Geol. Soc. America Ann. Mtg. (Milwaukee), Abs., p. 195-196.

Rye, R. O., and Ohmoto, H., 1974, Sulfur and carbon isotopes and ore genesis: a review: Econ. Geol., v. 69, p. 826-842.

Sakai, H., 1968, Isotopic properties of sulfur compounds in hydrothermal processes: Geochem. Jour., v. 2, p. 29-49.

Sangster, D. F., 1972, Precambrian volcanogenic massive sulfide deposits in Canada: Canada Geol. Survey, Paper 72-22, 44 p.

---- 1976, Sulphur and lead isotopes in stratabound deposits, in Wolf, K. H., ed., Handbook of Strata-Bound and Stratiform Ore Deposits, v. 2: New York, Elsevier Scientific Publishing Company, p. 219-266.

Sasaki, A., 1966, $\delta S^{34}$ values of meteoritic troilites: Unpublished research, University of Alberta, 1 p.

---- 1974, Isotopic data of Kuroko deposits, in Geology of Kuroko Deposits: Mining Geology Spec. Issue 6, Society of Mining Geologists of Japan, p. 389-397.

Sasaki, A., and Kajiwara, Y., 1971, Evidence of isotopic exchange between seawater sulfate and some syngenetic sulfide ores: Society of Mining Geologists of Japan, Spec. Issue 3, p. 289-294.

Sawkins, F. J., 1976, Massive sulfide deposits in relation to geotectonics, in Strong, D. F., ed., Metallogeny and Plate Tectonics: The Geological Association of Canada, Spec. Paper No. 14, p. 221-240.

Schouten, C., 1962, Determination tables for ore microscopy: New York, Elsevier Publishing Company, 242 p.

Selley, R. C., 1976, An introduction to sedimentology: San Francisco, Academic Press, 408 p.

Shimazaki, Y., 1974, Ore minerals of the Kuroko-type deposits: Mining Geology Spec. Issue 6, Society of Mining Geologists of Japan, p. 311-322.

Sinclair, A. J., 1976, Applications of probability graphs in mineral exploration: The Association of Exploration Geochemists, Special Volume No. 4, 95 p.

Smith, J. G., 1972, A Tertiary lamprophyre dike province in southeastern Alaska: Canadian Jour. Earth Sci., v. 10, p. 408-419.

Smith, R. E., and Smith, S. E., 1976, Comments on the use of Ti, Zr, Y, Sr, K, P and Nb in classification of basaltic magmas: Earth Planet. Sci. Letters., V. 32, p. 114-120.

Solomon, M., 1976, "Volcanic" massive sulphide deposits and their host rocks - a review and an explanation, in Wolf, K. H., ed., Handbook of Strata-bound and Stratiform Ore Deposits, v. 6: New York, Elsevier Scientific Publishing Company, p. 21-54.

---- and Walshe, J. L., 1979, The formation of massive sulfide deposits on the sea floor: Econ. Geol., v. 74, p. 797-813.

Souther, J. G., 1970, Volcanism and its relationship to recent crustal movements in the Canadian Cordillera: Canadian Jour. Earth Sci., v. 7, p. 553-568.

---- 1977, Volcanism and tectonic environments in the Canadian Cordillera - a second look, in Baragar, W. R. A., ed., Volcanic Regimes in Canada: The Geological Association of Canada, Special Paper Number 16, p. 3-24.

Spooner, E. T. C., and Fyfe, W. S., 1973, Sub-seafloor metamorphism, heat and mass transfer: Contr. Mineralogy Petrology, v. 42, p. 287-304.

Spry, A., 1969, Metamorphic textures: Oxford, Pergamon Press, 350 p.

Stanton, R. L., 1972, Ore petrology: New York, McGraw-Hill Book Company, 713 p.

Sutherland Brown, A., 1968, Geology of the Queen Charlotte Islands, British Columbia: B. C. Ministry of Energy, Mines and Pet. Res., Bull. 54.

Sutherland Brown, A., Cathro, R. J., Panteleyev, A., Ney, C. S., 1971, Metallogeny and the Canadian Cordillera: Canadian Inst. Mining Metallurgy, v. LXXIV, p. 121-145.

Tatsumi, T., 1970, ed., Volcanism and ore genesis: Tokyo, Univ. Tokyo Press.

Telfer, L., 1937, Anyox plant, Hidden Creek mine: Cominco Limited, Unpublished report.

Tipper, H. W., 1979, Personal communication.

Tipper, H. W., and Richards, T. A., 1976, Jurassic stratigraphy and history of north-central British Columbia: Canada Geol. Surv., Bull. 270, 69 p.

Thode, H. G., 1963, Sulphur isotope geochemistry, in Shaw, D. M., ed., Studies in Analytical Geochemistry: Royal Society of Canada Special Publication No. 6, p. 25-41.

Trudinger, P. A., 1976, Microbiological processes in relation to ore genesis, in Wolf, K. H., ed., Handbook of Strata-Bound and Stratiform Ore Deposits, v. 2: New York, Elsevier Scientific Publishing Company, p. 135-190.

Turner, J. S., and Gustafson, L. B., 1978, The flow of hot saline solutions from vents in the sea floor - some implications for exhalative massive sulfide and other ore deposits: Econ. Geol., v. 73, p. 1082-1100.

Urabe, T., and Sato, T., 1978, Kuroko deposits of the Kosaka mine, northeast Honshu, Japan - products of submarine hot springs on Miocene sea floor: Econ. Geol., v. 73, p. 161-179.

Urey, H. C., 1947, The thermodynamic properties of isotopic substances: Jour. Chem. Soc., p. 562-581.

Uytenbogaardt, W., and Burke, E. A. J., 1971, Tables for microscopic identification of ore minerals: New York, Elsevier Publishing Company, 430 p.

Vallette, J. N., 1976, Distribution of certain trace elements in marine sediments surrounding Vulcano Island (Italy), in Amstutz, G. C., and Bernard, A. J., eds., Ores in Sediments: New York, Springer-Verlag, p. 321-338.

Vokes, F. M., 1976, Caledonian massive sulphide deposits in Scandinavia: a comparative review, in Wolf, K. H., ed., Handbook of Strata-bound and Stratiform Ore Deposits, v. 6: New York, Elsevier Scientific Publishing Company, p. 79-127.

Vokes, F. M., and Gale, G. H., 1976, Metallogeny relatable to global tectonics in southern Scandinavia, in Strong, D. F., ed., Metallogeny and Plate Tectonics: Geological Association of Canada, Special Paper No. 14, p. 411-440.

Wheeler, J. O., Aitken, J. D., Berry, M. J., Gabrielse, H., Hutchison, W. W., Jacoby, W. R., Monger, J. W. H., Niblett, E. R., Norriss, D. K., Price, R. A., and Stacey, R. A., 1972, The Cordilleran structural province, in Price, R. A., and Douglas, R. J. W., eds., Variations in Tectonic Styles in Canada: The Geological Association of Canada, Special Paper No. 11, p. 1-82.

White, D. E., 1957, Magmatic, connate, and metamorphic waters: Bull. Geol. Soc. Amer., v. 69, p. 1860-1882.

Whitmore, D. R. E., 1952, Geological Report, No. 7 Orebody - Anyox: Cominco Limited, Unpublished report.

Winkler, H. G. F., 1974, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, 320 p.

Wise, S. H., Jr., and Weaver, F. M., 1974, Chertification of oceanic sediments, in Hsu, K. J., and Jenkyns, H. C., eds., Pelagic Sediments: One Land and Under the Sea: Oxford, Blackwell Scientific Publications, p. 301-326.

Woodcock, J. R., and Carter, N. C., 1976, Geology and geochemistry of the Alice Arm molybdenum deposits, in Sutherland Brown, A., ed., Porphyry Deposits of the Canadian Cordillera: The Canadian Inst. of Mining and Metallurgy, Spec. Vol. 15, p. 462-475.

# APPENDIX I

## ANALYTICAL RESULTS: MAJOR ELEMENT GEOCHEMISTRY
(Weight Percent)

| Sample No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | S | L.O.I. | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HC-16 | 53.02 | 13.30 | 2.21 | 9.14 | 6.69 | 7.32 | 3.98 | 0.24 | 1.72 | 0.18 | 0.06 | 0.11 | 97.97 |
| HC-17 | 46.45 | 14.92 | 1.89 | 11.16 | 7.69 | 10.27 | 2.48 | 0.22 | 1.78 | 0.31 | 0.36 | 0.75 | 98.28 |
| HC-18 | 45.01 | 17.41 | 1.98 | 10.36 | 6.19 | 11.72 | 1.76 | 0.89 | 1.22 | 0.18 | 0.13 | 0.98 | 97.83 |
| HC-19 | 48.01 | 15.87 | 2.78 | 8.24 | 7.23 | 6.87 | 3.88 | 0.38 | 1.82 | 0.27 | 0.23 | 2.34 | 97.92 |
| HC-20 | 49.93 | 15.41 | 2.30 | 7.48 | 6.56 | 8.39 | 3.59 | 0.63 | 1.67 | 0.29 | 0.24 | 2.38 | 98.87 |
| HC-21 | 54.73 | 13.53 | 2.22 | 8.68 | 5.22 | 8.19 | 2.74 | 0.22 | 1.29 | 0.23 | 0.26 | 1.04 | 98.35 |
| HC-22 | 50.45 | 15.81 | 2.06 | 7.70 | 6.19 | 7.95 | 4.32 | 0.07 | 1.68 | 0.29 | 0.56 | 1.46 | 98.54 |
| HC-23 | 50.87 | 16.47 | 0.74 | 6.84 | 5.27 | 6.31 | 5.41 | 0.24 | 1.71 | 0.30 | 1.14 | 3.88 | 99.18 |
| HC-25 | 52.51 | 13.98 | 1.24 | 9.12 | 7.42 | 6.99 | 2.98 | 0.57 | 1.75 | 0.18 | 0.93 | 2.75 | 100.42 |
| HC-26 | 60.41 | 10.28 | 1.00 | 6.80 | 5.51 | 7.22 | 1.61 | 0.31 | 1.28 | 0.09 | 0.40 | 2.36 | 97.27 |
| HC-27 | 57.51 | 12.16 | 0.70 | 8.84 | 6.22 | 8.09 | 1.89 | 0.36 | 1.39 | 0.14 | 0.57 | 1.21 | 99.08 |
| HC-28 | 48.17 | 14.97 | 1.39 | 10.90 | 8.04 | 9.66 | 1.75 | 0.19 | 1.84 | 0.21 | 0.16 | 0.71 | 97.99 |
| HC-29 | 55.12 | 12.08 | 2.96 | 6.22 | 7.16 | 8.59 | 2.23 | 0.13 | 1.69 | 0.15 | 0.76 | 2.18 | 99.27 |
| HC-30 | 48.41 | 14.49 | 1.98 | 11.24 | 7.96 | 8.27 | 1.30 | 0.13 | 1.90 | 0.18 | 0.11 | 2.08 | 98.05 |
| HC-31 | 50.95 | 13.62 | 0.77 | 11.20 | 9.32 | 6.22 | 2.95 | 0.07 | 1.79 | 0.18 | 0.04 | 0.71 | 97.82 |
| HC-32 | 49.29 | 13.34 | 0.80 | 11.84 | 9.27 | 7.71 | 2.66 | 0.06 | 1.87 | 0.15 | 0.07 | 0.87 | 97.93 |
| HC-33 | 47.95 | 14.04 | 1.46 | 11.66 | 11.54 | 3.84 | 1.51 | 0.01 | 2.01 | 0.20 | 0.03 | 3.65 | 97.90 |
| HC-34 | 44.92 | 13.52 | 5.14 | 14.72 | 10.18 | 0.97 | 0.75 | 0.01 | 1.11 | 0.09 | 0.43 | 5.99 | 97.83 |
| HC-35 | 52.64 | 10.89 | 1.50 | 17.86 | 7.10 | 0.63 | 0.48 | 0.01 | 1.28 | 0.09 | 0.76 | 4.79 | 98.03 |
| HC-36 | 42.33 | 13.86 | 5.59 | 17.78 | 9.45 | 0.50 | 0.64 | 0.03 | 1.69 | 0.14 | 0.11 | 5.48 | 97.60 |
| HC-37 | 42.94 | 13.86 | 5.91 | 14.46 | 10.16 | 1.02 | 0.64 | 0.01 | 1.69 | 0.16 | 1.22 | 6.19 | 98.26 |
| HC-38 | 59.21 | 9.56 | 3.51 | 6.50 | 7.67 | 7.28 | 0.98 | 0.27 | 1.37 | 0.09 | 0.74 | 2.88 | 100.06 |
| HC-40 | 50.27 | 14.32 | 1.42 | 10.00 | 9.18 | 4.96 | 3.28 | 0.04 | 1.50 | 0.15 | 0.07 | 2.36 | 97.55 |
| HC-41 | 46.03 | 12.67 | 3.12 | 11.14 | 10.74 | 7.21 | 1.35 | 0.15 | 1.43 | 0.15 | 1.12 | 2.57 | 97.68 |
| HC-42 | 57.87 | 13.24 | 2.19 | 6.02 | 6.53 | 5.34 | 3.50 | 0.34 | 1.46 | 0.17 | 0.09 | 2.17 | 98.92 |
| HC-43 | 49.51 | 15.17 | 0.01 | 10.00 | 6.93 | 12.18 | 2.34 | 0.15 | 1.39 | 0.21 | 0.40 | 0.74 | 99.03 |
| HC-44 | 50.24 | 15.01 | 0.89 | 7.88 | 8.12 | 11.42 | 2.45 | 0.42 | 1.19 | 0.15 | 0.03 | 0.76 | 98.56 |
| HC-45 | 49.61 | 14.51 | 1.34 | 9.36 | 7.88 | 10.33 | 2.47 | 0.60 | 1.74 | 0.21 | 0.05 | 0.75 | 98.85 |
| HC-46 | 60.67 | 12.38 | 2.14 | 7.90 | 3.09 | 5.56 | 3.50 | 0.11 | 1.73 | 0.39 | 0.41 | 1.50 | 99.38 |

APPENDIX I, CONTINUED

| Sample No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | S | L.O.I. | $H_2O^-$% | $H_2O+$% | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S-515 | 47.28 | 15.40 | 2.70 | 9.57 | 8.53 | 10.38 | 2.73 | 0.52 | 1.45 | 0.20 | 0.01 | 1.48 | 0.08 | 1.00 | 99.85 |
| S-531 | 48.33 | 14.68 | 2.52 | 9.05 | 8.42 | 11.15 | 2.61 | 0.10 | 1.41 | 0.18 | 0.05 | 0.83 | 0.09 | 1.22 | 99.81 |
| S-537 | 48.84 | 15.80 | 2.82 | 5.94 | 9.39 | 11.91 | 2.40 | 0.15 | 1.05 | 0.15 | 0.04 | 1.70 | 0.03 | 1.42 | 99.74 |
| S-540A | 47.41 | 14.63 | 3.33 | 8.67 | 8.05 | 12.65 | 2.15 | 0.12 | 1.23 | 0.15 | 0.43 | 1.62 | 0.02 | 1.24 | 100.08 |
| S-550A | 49.10 | 16.25 | 2.10 | 7.94 | 7.84 | 10.40 | 3.14 | 0.18 | 1.37 | 0.19 | 0.24 | 1.61 | 0.07 | 1.20 | 100.02 |
| S-553 | 44.72 | 15.53 | 2.76 | 8.60 | 10.73 | 11.50 | 1.31 | 0.92 | 1.14 | 0.15 | 0.19 | 2.36 | 0.15 | 2.36 | 100.06 |
| S-561 | 50.02 | 12.62 | 2.99 | 8.98 | 8.49 | 10.95 | 2.62 | 0.23 | 1.53 | 0.19 | – | 1.67 | 0.10 | 1.18 | 99.90 |
| S-565 | 47.93 | 14.31 | 2.88 | 8.68 | 8.24 | 12.86 | 2.11 | 0.11 | 1.45 | 0.17 | – | 1.42 | 0.01 | 1.10 | 99.85 |
| S-578 | 47.29 | 15.21 | 3.42 | 8.39 | 7.72 | 12.56 | 2.31 | 0.29 | 1.26 | 0.14 | – | 1.59 | 0.01 | 1.26 | 99.86 |
| S-580 | 46.72 | 14.46 | 4.32 | 6.15 | 7.75 | 15.95 | 1.83 | 0.19 | 1.12 | 0.09 | – | 2.70 | 0.03 | 1.40 | 100.01 |
| A-11 | 45.73 | 14.29 | 5.10 | 8.02 | 8.00 | 13.50 | 1.79 | 0.30 | 1.63 | 0.17 | 0.31 | 1.56 | 0.01 | 1.32 | 100.17 |
| A-25 | 47.11 | 15.93 | 6.19 | 5.05 | 8.99 | 10.12 | 2.95 | 0.49 | 1.26 | 0.18 | 0.02 | 1.79 | 0.07 | 1.90 | 100.26 |
| U7-86 | 46.69 | 16.87 | 1.37 | 10.08 | 9.07 | 10.78 | 2.41 | 0.74 | 1.45 | 0.26 | – | 0.52 | – | – | 100.24 |
| U4-91 | 50.70 | 17.34 | 1.62 | 7.48 | 7.91 | 8.37 | 4.52 | 0.41 | 1.31 | 0.20 | – | 0.74 | – | – | 100.60 |
| U4-202.5 | 49.13 | 18.08 | 1.72 | 8.36 | 7.83 | 9.59 | 3.51 | 0.42 | 1.32 | 0.22 | – | 0.41 | – | – | 100.59 |
| U14-580.5 | 48.67 | 16.48 | 1.72 | 8.76 | 7.60 | 11.58 | 3.26 | 0.28 | 1.27 | 0.25 | – | 0.23 | – | – | 100.10 |
| A-14 | 49.75 | 15.48 | 1.08 | 9.64 | 7.25 | 11.44 | 3.44 | 0.20 | 1.37 | 0.26 | – | 0.25 | – | – | 100.16 |
| A-15 | 49.00 | 16.29 | 1.11 | 9.40 | 7.26 | 12.23 | 3.24 | 0.22 | 1.46 | 0.28 | – | 0.42 | – | – | 100.91 |
| S-518 | 47.14 | 18.69 | 1.62 | 9.96 | 8.80 | 5.54 | 2.81 | 0.19 | 1.77 | 0.29 | – | 3.25 | – | – | 100.06 |
| S-579 | 48.85 | 19.81 | 1.69 | 5.56 | 5.65 | 13.99 | 3.07 | 0.38 | 0.74 | 0.24 | – | 0.82 | – | – | 100.80 |
| S-147 | 51.08 | 18.02 | 1.78 | 6.88 | 6.17 | 8.78 | 4.87 | 0.71 | 1.73 | 0.38 | – | 0.45 | – | – | 100.85 |

# APPENDIX II

## ROCK GEOCHEMISTRY: SAMPLING AND PREPARATION

### Sampling Procedure

Rock samples were collected from outcrop and diamond drill core in the Anyox area; samples were usually 1 kg rock chips broken by hammer, or 0.3 m lengths of diamond drill core weighing 1 kg. The samples were stored in numbered plastic bags. An effort was made to get the most representative material from each location sampled.

### Sample Preparation

Samples prepared at the University of Alberta were first crushed to minus 1.2 cm in a jaw crusher, then were finely powdered in a Tema swingmill. Sample powders were sent to Dr. G. Holland, Durham University in England and to Dr. J. Harris, Cominco Research Laboratory, Vancouver, British Columbia.

# APPENDIX III

## ROCK GEOCHEMISTRY: ANALYTICAL TECHNIQUES

### MAJOR ELEMENT ANALYTICAL TECHNIQUES

#### Cominco Limited Research Laboratory

At the research laboratory of Cominco Limited, major element analyses of rock powders are carried out as follows:

A 2 g sample is roasted for one hour at 900°C to determine the percentage weight loss on ignition (L.O.I.). The roasted sample is mixed with 7 g of a proprietary flux (composed of lithium metaborate, lithium carbonate and lanthanum oxide) and fused for one hour at 1100°C in a muffle furnace. The charge is then poured into graphite molds and allowed to solidify as glass discs 4.0 cm in diameter. These discs are given a fine grind on a diamond wheel to ensure flatness and surface uniformity, and are then analyzed on a Siemens SRS X-Ray fluoresence analysis unit, calibrated against 22 international standard rocks. Necessary curve corrections and inter-element corrections are applied automatically (pre-programmed into the computer) and a readout of true concentrations is obtained. Precision for all elements is generally within ±2% (J. Harris, personal communication). FeO was determined, using a standard dichromate titration (J. Harris, personal communication).

#### University of Durham, England

Rock powders were analyzed by X-Ray fluoresence for major elements plus S, Cu, Zn, Ni, Cr, Ba, Nb, Zr, Y and Rb. Analyses for $H_2O^-$, $H_2O^+$,

L.O.I., and FeO were performed by the writer at the University of Alberta. One gram of sample powder was placed in a platinum crucible and heated to 110°C for 10 to 12 hours, cooled in a dessicator, then weighed to obtain $H_2O^-$ of the sample. A 1 g sample was place in a platinum crucible and roasted in a furnace at 1000°C for one hour, cooled and weighed to obtain L.O.I. values. Values for $H_2O^+$ were obtained using the Penfield method of water analysis. FeO content of the samples was determined by titration with potassium permanganate after decomposition in sulfuric and hydrofluoric acids.

## TRACE ELEMENT GEOCHEMISTRY

### Cominco Limited Research Laboratory

Samples were crushed in a ceramic system and and analyzed for Cu, Pb, Zn, Mn, and Ag by atomic absorption spectrophotometry after a nitric-perchloric acid digestion. Values are reproducable to ±10% of the contained amount of the unknown element. Gold was analyzed by atomic absorption sprectrophotometry after digestion in aqua-regia; barium was analyzed by X-Ray fluoresence spectrometry; sulfur was analyzed using a Leco automatic sulfur titrator. Mercury analyses were obtained by digestion of the sample in aqua-regia, with $SnCl_2$ added to produce free Hg, then the sample was bubbled and the vapor analyzed by atomic absorption (Osatenko, 1977).

# APPENDIX IV-a

## STANDARD CELL SAMPLE CALCULATION FOR UNALTERED METABASALT

| Oxide | Weight Percent | Molecular Weight | Molecular Proportion | Atomic Proportion Oxygen | Atomic Proportion Oxygen x 1000 | Standard Cell Oxygen | Cations in Standard Cell |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48.51 | 60.08 | 0.8074 | 1.61485 | 1614.85 | 93.73 | 46.9 |
| $Al_2O_3$ | 14.90 | 101.96 | 0.1461 | 0.43841 | 438.41 | 25.44 | 17.0 |
| $Fe_2O_3$ | 2.21 | 159.69 | 0.0063 | 0.01879 | 18.79 | 1.09 | 0.7 |
| FeO | 9.21 | 71.85 | 0.1282 | 0.12818 | 128.18 | 7.44 | 7.4 |
| MgO | 8.04 | 40.31 | 0.1994 | 0.19945 | 199.45 | 11.58 | 11.6 |
| CaO | 11.56 | 56.08 | 0.2061 | 0.20613 | 206.13 | 11.96 | 12.0 |
| $Na_2O$ | 2.40 | 61.98 | 0.0387 | 0.03872 | 38.72 | 2.25 | 4.5 |
| $K_2O$ | 0.24 | 94.20 | 0.0026 | 0.00255 | 2.55 | 0.15 | 0.3 |
| $TiO_2$ | 1.40 | 79.90 | 0.0175 | 0.03504 | 35.04 | 2.03 | 1.0 |
| $P_2O_5$ | 0.18 | 141.94 | 0.0013 | 0.00634 | 6.34 | 0.37 | 0.2 |
| $H_2O$ | 1.23 | 18.02 | 0.0683 | 0.06826 | 68.26 | 3.96 | (7.9) |
| S | 0.12 | 32.06 | 0.0037 | - | - | - | - |
| TOTAL | 100.00 | | | | 2756.72 | 160.00 | 101.6 |

# APPENDIX IV-b

## ROCK ALTERATION

### UNALTERED METABASALTIC ROCKS

Pillowed Lava Flows

| Sample No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | S | L.O.I. | $H_2O$ | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hidden Creek Deposit | | | | | | | | | | | | | | |
| HC-17 | 49.51 | 15.17 | 0.01 | 10.00 | 6.93 | 12.18 | 2.34 | 0.15 | 1.39 | 0.21 | 0.40 | 0.74 | - | 99.73 |
| HC-43 | 46.45 | 14.92 | 1.89 | 11.16 | 7.69 | 10.27 | 2.48 | 0.22 | 1.78 | 0.31 | 0.36 | 0.75 | - | 99.16 |
| HC-44 | 50.24 | 15.01 | 0.89 | 7.88 | 8.12 | 11.42 | 2.45 | 0.42 | 1.19 | 0.15 | 0.03 | 0.76 | - | 99.41 |
| HC-45 | 49.61 | 14.51 | 1.34 | 9.36 | 7.88 | 10.33 | 2.47 | 0.60 | 1.74 | 0.21 | 0.05 | 0.75 | - | 99.85 |
| O-274 | 48.84 | 14.96 | 1.77 | 8.12 | 7.57 | 12.71 | 2.27 | 0.19 | 1.15 | 0.14 | 0.08 | 0.46 | - | 99.08 |
| O-275B | 49.53 | 12.82 | 1.35 | 10.70 | 7.65 | 12.36 | 1.68 | 0.06 | 1.42 | 0.17 | 0.01 | 0.62 | - | 99.55 |
| O-276 | 48.67 | 14.64 | 4.37 | 11.06 | 7.13 | 8.94 | 2.97 | 0.05 | 1.82 | 0.21 | 0.03 | 0.56 | - | 101.65 |
| O-278 | 48.67 | 15.28 | 2.04 | 10.20 | 8.22 | 9.73 | 2.85 | 0.28 | 1.51 | 0.17 | 0.22 | 0.87 | - | 100.96 |
| Mean | 48.98 | 14.66 | 1.71 | 9.80 | 7.65 | 10.99 | 2.44 | 0.25 | 1.50 | 0.20 | 0.15 | 0.69 | - | 99.92 |
| Double Ed Deposit | | | | | | | | | | | | | | |
| S-515 | 47.28 | 15.40 | 2.96 | 9.34 | 8.53 | 10.38 | 2.73 | 0.52 | 1.45 | 0.20 | 0.01 | 1.48 | 1.00 | 99.80 |
| S-537 | 48.84 | 15.80 | 2.08 | 6.61 | 9.39 | 11.91 | 2.40 | 0.15 | 1.05 | 0.15 | 0.04 | 1.70 | 1.42 | 99.92 |
| S-540 | 47.41 | 14.63 | 2.87 | 9.09 | 8.05 | 12.65 | 2.15 | 0.12 | 1.23 | 0.15 | 0.43 | 1.62 | 1.24 | 100.02 |
| S-565 | 47.93 | 14.31 | 2.78 | 8.77 | 8.24 | 12.86 | 2.11 | 0.11 | 1.45 | 0.17 | 0.00 | 1.42 | 1.10 | 99.83 |
| S-578 | 47.29 | 15.21 | 2.82 | 8.93 | 7.72 | 12.56 | 2.31 | 0.29 | 1.26 | 0.14 | 0.00 | 1.26 | 1.26 | 99.79 |
| Mean | 45.75 | 15.07 | 2.70 | 8.55 | 8.39 | 12.07 | 2.34 | 0.24 | 1.29 | 0.16 | 0.10 | 1.50 | 1.20 | 99.87 |
| Composite Mean | 48.36 | 14.86 | 2.20 | 9.18 | 8.02 | 11.53 | 2.39 | 0.24 | 1.40 | 0.18 | 0.12 | 1.10 | 1.20 | 99.68 |

APPENDIX IV-b, CONTINUED

ROCK ALTERATION

WEAKLY ALTERED METABASALTIC ROCKS

Pillowed Lava Flows

| Sample No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | S | L.O.I. | $H_2O$ | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HC-25 | 52.51 | 13.98 | 1.24 | 9.12 | 7.42 | 6.99 | 2.98 | 0.57 | 1.75 | 0.18 | 0.93 | 2.75 | - | 100.51 |
| HC-26 | 60.41 | 10.28 | 1.00 | 6.80 | 5.51 | 7.22 | 1.61 | 0.31 | 1.28 | 0.09 | 0.40 | 2.36 | - | 97.63 |
| HC-28 | 48.17 | 14.97 | 1.39 | 10.90 | 8.04 | 9.66 | 1.75 | 0.19 | 1.84 | 0.21 | 0.16 | 0.71 | - | 99.04 |
| HC-29 | 55.12 | 12.08 | 2.96 | 6.22 | 7.16 | 8.59 | 2.22 | 0.13 | 1.69 | 0.15 | 0.76 | 2.18 | - | 99.20 |
| HC-31 | 50.95 | 13.62 | 0.77 | 11.20 | 9.32 | 6.22 | 2.95 | 0.07 | 1.79 | 0.18 | 0.04 | 0.71 | - | 99.03 |
| HC-32 | 49.24 | 13.34 | 0.80 | 11.84 | 9.27 | 7.71 | 2.66 | 0.06 | 1.87 | 0.15 | 0.07 | 0.87 | - | 99.18 |
| HC-40 | 50.27 | 14.32 | 1.42 | 10.00 | 9.18 | 4.96 | 3.28 | 0.04 | 1.50 | 0.15 | 0.07 | 2.36 | - | 98.59 |
| HC-41 | 46.03 | 12.67 | 3.12 | 11.14 | 10.74 | 7.21 | 1.35 | 0.15 | 1.43 | 0.15 | 1.12 | 2.57 | - | 97.80 |
| S-531 | 48.33 | 14.68 | 2.52 | 9.05 | 8.42 | 11.15 | 2.61 | 0.10 | 1.41 | 0.18 | 0.05 | 0.83 | - | 100.29 |
| Mean | 51.23 | 13.33 | 1.69 | 9.59 | 8.34 | 7.75 | 2.38 | 0.18 | 1.62 | 0.16 | 0.40 | 1.70 | - | 98.85** |
| STRONGLY ALTERED METABASALTIC ROCKS | | | | | | | | | | | | | | |
| Pillowed Lava Flows | | | | | | | | | | | | | | |
| HC-33 | 47.95 | 14.04 | 1.46 | 11.66 | 11.54 | 3.84 | 1.51 | 0.01 | 2.01 | 0.20 | 0.03 | 3.65 | - | 99.17 |
| HC-34 | 44.92 | 13.52 | 5.14 | 14.72 | 10.18 | 0.97 | 0.75 | 0.01 | 1.11 | 0.09 | 0.43 | 5.99 | - | 99.04 |
| HC-36 | 42.33 | 13.86 | 5.59 | 17.78 | 9.45 | 0.50 | 0.64 | 0.03 | 1.69 | 0.14 | 0.11 | 5.48 | - | 99.47 |
| HC-37 | 42.94 | 13.86 | 5.91 | 14.46 | 10.16 | 1.02 | 0.64 | 0.01 | 1.69 | 0.16 | 1.22 | 6.19 | - | 98.65 |
| HC-38 | 59.21 | 9.56 | 3.51 | 6.50 | 7.67 | 7.28 | 0.98 | 0.27 | 1.37 | 0.09 | 0.74 | 2.88 | - | 100.04 |
| S-518 | 47.14 | 18.69 | 1.62 | 9.96 | 8.80 | 5.54 | 2.81 | 0.19 | 1.77 | 0.29 | 1.50* | 3.25 | - | 99.67 |
| Mean | 47.42 | 13.92 | 3.87 | 12.51 | 9.63 | 3.19 | 1.22 | 0.36 | 1.61 | 0.06 | 0.51 | 4.57 | - | 98.85** |

*Estimates
**After L.O.I. Correction

APPENDIX IV-b, CONTINUED

ROCK ALTERATION

WEAKLY ALBITIZED METABASALTIC ROCKS

Pillowed Lava Flows

| Sample No. | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ | S | L.O.I. | $H_2O$ | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HC-16 | 53.02 | 13.30 | 2.21 | 9.14 | 6.69 | 7.32 | 3.98 | 0.24 | 1.72 | 0.18 | 0.06 | 0.11 | - | 98.93 |
| HC-19 | 48.01 | 15.87 | 2.78 | 8.24 | 7.23 | 6.87 | 3.88 | 0.38 | 1.82 | 0.27 | 0.23 | 2.34 | - | 98.61 |
| HC-20 | 49.93 | 15.41 | 2.30 | 7.48 | 6.56 | 8.39 | 3.59 | 0.63 | 1.67 | 0.29 | 0.24 | 2.38 | - | 99.46 |
| HC-21 | 54.73 | 13.53 | 2.22 | 8.68 | 5.22 | 8.19 | 2.74 | 0.22 | 1.29 | 0.23 | 0.26 | 1.04 | - | 99.06 |
| HC-22 | 50.45 | 15.81 | 2.06 | 7.70 | 6.19 | 7.95 | 4.32 | 0.07 | 1.68 | 0.29 | 0.56 | 1.46 | - | 98.84 |
| HC-23 | 50.87 | 16.47 | 0.74 | 6.84 | 5.27 | 6.31 | 5.41 | 0.24 | 1.71 | 0.30 | 1.14 | 3.88 | - | 98.80 |
| HC-42 | 57.87 | 13.24 | 2.19 | 6.02 | 6.53 | 5.34 | 3.50 | 0.34 | 1.46 | 0.17 | 0.09 | 2.17 | - | 99.50 |
| HC-46 | 60.67 | 12.38 | 2.14 | 7.90 | 3.09 | 5.56 | 3.50 | 0.11 | 1.73 | 0.39 | 0.41 | 1.50 | - | 99.85 |
| U4-91 | 50.70 | 17.34 | 1.62 | 7.48 | 7.91 | 8.37 | 4.52 | 0.41 | 1.31 | 0.20 | 0.65* | 0.74 | - | 100.78 |
| U4-202.5 | 49.13 | 18.08 | 1.72 | 8.36 | 7.83 | 9.59 | 3.51 | 0.42 | 1.32 | 0.22 | 0.55* | 0.41 | - | 100.97 |
| S-550A | 49.10 | 16.25 | 2.10 | 7.94 | 7.84 | 10.40 | 3.14 | 0.18 | 1.37 | 0.19 | 0.24 | 1.61 | - | 100.60 |
| Mean | 52.22 | 15.24 | 2.01 | 7.80 | 6.40 | 7.66 | 3.83 | 0.29 | 1.55 | 0.25 | 0.40 | 1.60 | - | 98.68** |

*Estimates
**After L.O.I. Correction

# APPENDIX IV-c

## AVERAGE ANALYSES OF PILLOWED METABASALTIC LAVA

(Corrected to 100 Weight Percent)

| | UNALTERED | WEAKLY ALTERED | STRONGLY ALTERED | WEAKLY ALBITIZED |
|---|---|---|---|---|
| $SiO_2$ | 48.51 | 52.07 | 47.92 | 52.62 |
| $Al_2O_3$ | 14.90 | 13.55 | 14.06 | 15.36 |
| $Fe_2O_3$ | 2.21 | 1.72 | 3.91 | 2.02 |
| FeO | 9.21 | 9.75 | 12.64 | 7.86 |
| MgO | 8.04 | 8.48 | 9.73 | 6.45 |
| CaO | 11.56 | 7.88 | 3.22 | 7.72 |
| $Na_2O$ | 2.40 | 2.42 | 1.23 | 3.86 |
| $K_2O$ | 0.24 | 0.18 | 0.36 | 0.29 |
| $TiO_2$ | 1.40 | 1.65 | 1.63 | 1.56 |
| $P_2O_5$ | 0.18 | 0.16 | 0.16 | 0.25 |
| $H_2O$ | 1.23 | 1.73 | 4.62 | 1.61 |
| S | 0.12 | 0.41 | 0.52 | 0.40 |
| TOTAL | 100.00 | 100.00 | 100.00 | 100.00 |

# APPENDIX V

## COPPER GEOCHEMISTRY: DOUBLE ED

| Sample No. | PPM Cu | Rock Type |
|---|---|---|
| **SURFACE SAMPLES** | | |
| S-515 | 77 | Pillowed Metabasalt |
| S-531 | 84 | Pillowed Metabasalt |
| S-553C | 24 | Impure Quartzite |
| S-533D | 23 | Biotite-Chlorite Schist |
| S-537 | 58 | Pillowed Metabasalt |
| S-540 | 106 | Pillowed Metabasalt |
| S-550A | 36 | Metabasaltic Tuff |
| S-550B | 45 | Metapelite |
| S-550C | 6 | Metapelite |
| S-548 | 14 | Metapelite |
| S-551 | 165 | Metabasaltic Agglomerate |
| S-553 | 78 | Amphibolite Intrusive |
| S-561 | 10 | Metabasaltic Tuff |
| S-565 | 16 | Pillowed Metabasalt |
| S-571A | 36 | Metabasaltic Tuff and Metapelite |
| S-578 | 89 | Pillowed Metabasalt |
| S-580 | 41 | Pillowed Metabasalt |
| S-584 | 7 | Impure Quartzite |
| S-585A | 18 | Impure Quartzite |
| S-586A | 56 | Impure Quartzite |
| **SURFACE DIAMOND DRILL HOLES** | | |
| S6-89.5 | 125 | Pillowed Metabasalt |
| S6-108 | 224 | Altered Metapelite |
| S6-146 | 3870 | Massive Sulfide Zone |
| S6-192 | 108 | Metabasaltic Tuff |
| S6-204 | 173 | Metabasaltic Tuff |
| S6-255 | 161 | Pillowed Metabasalt |
| S6-339 | 90 | Metabasaltic Agglomerate |
| S6-370 | 2830 | Massive Sulfide Zone |
| S6-397 | 116 | Metabasaltic Agglomerate |
| S7-149 | 157 | Altered Metapelite |
| S7-206 | 164 | Metabasaltic Tuff |
| S7-236.5 | 550 | Metabasaltic Tuff and Metapelite |
| S7-306 | 670 | Metabasaltic Tuff and Metapelite |
| S7-376 | 1220 | Metabasaltic Tuff and Metapelite |

# APPENDIX VI

## TRACE ELEMENT DATA FROM ORE HORIZON QUARTZITE AT ANYOX

| Sample | Parts Per Million | | | | | | Parts Per Billion | | Weight Percent | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Cu | Zn | Pb | Mn | Ba | Ag | Au | Hg | S | Fe |
| HC-61 | 54 | 37 | 3 | - | - | - | - | - | 2.3 | 4.8 |
| Hc-60 | 28 | 80 | 3 | - | - | - | - | - | 1.7 | 7.1 |
| HC-59 | 53 | 58 | 3 | - | - | - | - | - | 2.3 | 6.8 |
| HC-58 | 29 | 35 | 5 | - | - | - | - | - | 0.3 | 4.0 |
| HC-57 | 344 | 16 | 3 | 57 | 327 | 0.3 | 10 | 5 | 0.8 | 5.5 |
| HC-39 | 60 | 25 | 3 | 178 | 324 | 0.3 | 10 | 5 | 0.6 | 4.1 |
| HC-47 | 164 | 103 | 3 | 400 | 937 | 0.3 | 10 | 5 | 1.0 | 2.7 |
| HC-48 | 268 | 41 | 3 | 163 | 412 | 0.6 | 10 | 5 | 1.2 | 2.8 |
| HC-49 | 186 | 12 | 3 | 15 | 684 | 0.3 | 10 | 5 | 3.2 | 3.8 |
| HC-7 | 32 | 118 | 5 | 305 | 436 | 0.3 | 10 | 10 | 0.3 | 1.3 |
| HC-50 | 22 | 4 | 4 | 18 | 461 | 0.7 | 20 | 35 | 0.2 | 0.7 |
| HC-51 | 23 | 15 | 3 | 21 | 540 | 0.5 | 10 | 80 | 3.5 | 3.3 |
| HC-52 | 57 | 240 | 3 | 482 | 737 | 0.4 | 10 | 5 | 0.9 | 3.5 |
| HC-53 | 181 | 164 | 3 | 150 | 329 | 4.2 | 40 | 5 | 2.0 | 5.0 |
| HC-54 | 30 | 17 | 4 | 110 | 316 | 0.3 | 10 | 5 | 0.1 | 7.7 |
| HC-55 | 1300 | 56 | 3 | 100 | 498 | 1.5 | 10 | 5 | 1.9 | 3.1 |
| HC-56 | 451 | 95 | 10 | - | - | - | - | - | N.A.* | 12.5 |
| HC-24 | 175 | 57 | 3 | - | - | - | - | - | 1.8 | 3.6 |

*No data available

# APPENDIX VII-a

## SULFUR ISOTOPE ANALYSES: PREPARATION OF SAMPLES

### 1. Selection

Samples were selected for sulfur isotope analysis on the basis of abundance of sulfide minerals, the location of the sample, and the presence of co-existing sulfide minerals. All samples were examined optically using a binocular microscope, and descriptions were recorded. Polished sections of a number of samples were also made and described. Sample descriptions are not included in this thesis, but are available from the writer.

### 2. Crushing and Sizing

Weathered material was cut from the samples with a diamond saw. The samples were crushed in a jaw crusher, then powdered in a swing-mill for 20 to 30 seconds. Crushed samples were screened and the minus 140 plus 270 mesh fraction was taken for further purification of the sulfide minerals while oversized and undersized material was stored separately.

### 3. Sulfide Purification

The sized sample was deslimed by mixing with cool water in a large beaker and decanting the supernatant liquid containing the fine-grained particles in suspension which adhered to the mineral grains during crushing and screening steps. The deslimed sample was rinsed onto filter paper and dried (Hutchison, 1974).

Heavy liquids were used to separate the silicate from the sulfide minerals. Methylene iodide (specific gravity 3.3) was placed in a separatory funnel, the sample was added, stirred, and left for approximately one hour, or until a proper separation of "lights" and "heavies" occurred. The heavy fraction contained the sulfide minerals and was drawn off, washed with acetone until all of the methylene iodide was removed, then dried.

A hand magnet was used to remove iron filings, magnetite, and magnetic pyrrhotite from the sample. The sample was passed through a Franz isodynamic magnetic separator. A variety of amperage settings, plus forward and sideways tilts were used to effect a proper separation of the sulfide minerals in each sample. Purity of mineral concentrates, chalcopyrite, pyrite or sphalerite, was better than 90% before hand picking was attempted. Approximately 50 mg of the +90% concentrate was hand picked, using a microscope and needle, to +98% purity. Sample purity was evaluated optically using the binocular microscope.

The separation procedures used in the sulfide purification steps are all physical, hence no chemically induced sulfur isotopic fractionation could have occurred. The sulfide minerals of one type were homogenized, but not fractionated. If two generations of one particular type of sulfide mineral were present in the bulk sample, the isotopic analysis will reflect the average isotopic value of the two samples.

4. Sulfide Oxidation

Sulfur dioxide gas was produced by direct oxidation of the purified sulfide sample in a quartz-pyrex combustion line. Purified cuprous oxide

(heated at 500°C for 24 hours under vacuum and later finely ground, then stored) was the oxidant which was mixed with a precisely weighed sulfide sample that had been ground in an agate mortar. A measured amount of sulfide was reacted with the cuprous oxide to produce 250 micromoles of $SO_2$ gas. The sample was placed in a cylindrical, hollow wuartz sample chamber packed with quartz wool at both ends, then inserted into a removable quartz tube attached to the $SO_2$ gas extraction line. The system was slowly pumped down to a high vacuum by a roughing and mercury diffusion pump system. When a stable vacuum condition was reached, the pumping system was valved off, the furnace was heated to 1000°C, and the sample was inserted into the furnace, using a quartz boat and magnet. At 1000°C, the cuprous oxide reacts with the sulfide to produce sulfur dioxide, carbon dioxide and water vapor. The gases were passed through a cold trap (surrounded by dry ice and ethanol at a temperature of -40°C) which froze out the water, but allowed $SO_2$ and $CO_2$ to pass on to a second cold trap (surrounded by liquid nitrogen at -195°C) where the two gases froze. When the oxidation reaction was completed, the combustion line and water trap were valved off. The $CO_2$ and $SO_2$ were separated using Mizutani and Oana's (1973) technique where the liquid nitrogen was removed and the sample was allowed to expand to room temperature, then a frozen n-Pentane cold trap was applied to the sample chamber. At the temperature of frozen n-Pentane (-130.8°C), $SO_2$ freezes, while $CO_2$ remains gaseous and may be pumped out of the system. The vacuum line was valved off, the $SO_2$ yield was measured, using a mercury breakseal tube. The breakseal tubes were then stored for spectrometric analysis (Kuo, 1977).

# APPENDIX VII-b

## SULFUR ISOTOPE ANALYSES: MASS SPECTROMETRY

The sulfur dioxide gas from the sulfide sample was analyzed by Dr. H. R. Krouse, Professor of Physics at the University of Calgary, using a mass spectrometer built around a micromass 602 analyzer. In the mass spectrometer, the $SO_2$ sample was introduced through a magnetic value system which alternately switched between a reference $SO_2$ sample and the unknown sample. Ion currents of mass 64 and 65 were digitally printed. Corrections were made for oxygen isotope composition of mass 66 ($^{32}S^{16}O^{18}O$ and $^{34}S^{16}O_2$). The sulfur isotope composition was reported using the traditional $\delta^{34}S$ scale of:

$$\delta^{34}S\,(‰) = \frac{^{34}S/^{32}S\ \text{SAMPLE} - 1}{^{34}S/^{32}S\ \text{STANDARD}} \times 10^3$$

Standard $SO_2$ gas samples were collected and analyzed. The results are given in Appendix VII-c. Analytical results of the samples are listed in Appendix VII-d. The oxygen correction factors between the University of Alberta sulfur dioxide gas preparation laboratory and the one at the University of Calgary differ, therefore all results are referred to the first run of the Mayerthorpe Troilite Standard having $\delta^{34}S = 0‰$. The standard deviations of the analyses are better than 0.1‰ with repeats very close (H. R. Krouse, personal communication).

# APPENDIX VII-c

## SULFUR ISOTOPE STANDARD ANALYSES

| Number | Sample Number | Sample Type | Measured $\delta^{34}S$ ‰ |
|---|---|---|---|
| 1 | Mayerthorpe T-1 | Troilite | 0.0 |
| 2 | Mayerthrope T-2 | Troilite | 0.0 |
| 3 | Mayerthrope T-3 | Troilite | -0.2 |
| 4 | NBS #120 | Native Sulfur | +1.4 |
| 5 | NBS #120 | Native Sulfur | +1.5 |
| 6 | NBS #120 | Native Sulfur | +1.2 |
| 7 | NBS #120 | Native Sulfur | +1.2 |
| 8 | NBS #120 | Native Sulfur | +1.0 |
| 9 | NBS #120 | Native Sulfur | +1.1 |
| 10 | ZNS (Pine Point) | Sphalerite | +22.2 |
| 11 | ZNS (Pine Point) | Sphalerite | +22.1 |
| 12 | ZNS (Pine Point) | Sphalerite | +22.2 |
| 13 | Zns (Pine Point) | Sphalerite | +22.1 |
| 14 | U13-166 | Pyrite | +3.9 |
| 15 | U13-166 | Pyrite | +3.9 |
| 16 | U13-166 | Pyrite | +3.7 |
| 17 | U13-166 | Pyrite | +3.7 |

All samples prepared at the University of Alberta.

Mass spectrometry performed at the University of Calgary.

APPENDIX VII-d

SULFUR ISOTOPE RESULTS

| NO. | SAMPLE NO. | DEPOSIT | YIELD % | PYRITE $S^{34}S$ (‰) | YIELD % | CHALCOPYRITE $S^{34}S$ (‰) | YIELD % | SPHALERITE $S^{34}S$ (‰) |
|---|---|---|---|---|---|---|---|---|
| 1 | U2-243 | Double Ed | 93.3 | +4.8 | 97.7 | +3.6 | – | – |
| 2 | U2-250.5 | Double Ed | 92.9 | +4.3 | – | – | – | – |
| 3 | U2-262 | Double Ed | 95.7 | +4.9 | 103.7 | +4.3 | – | – |
| 4 | U2-279 | Double Ed | 96.0 | +4.6 | – | – | – | – |
| 5 | U2-295 | Double Ed | 95.6 | +3.9 | 96.7 | +3.6 | – | – |
| 6 | U2-358 | Double Ed | 97.0 | +4.4 | – | – | – | – |
| 7 | U2-360 | Double Ed | 93.7 | +4.2 | 98.4 | +3.8 | – | – |
| 8 | U2-376 | Double Ed | 91.6 | +4.8 | – | – | – | – |
| 9 | U2-391 | Double Ed | 94.2 | +4.8 | – | – | – | – |
| 10 | U2-403 | Double Ed | 97.2 | +4.6 | – | – | – | – |
| 11 | U2-415.5 | Double Ed | 95.1 | +4.6 | – | – | – | – |
| 12 | U13-57.5 | Double Ed | 93.6 | +3.0 | – | – | – | – |
| 13 | U13-76 | Double Ed | – | – | 100.7 | +3.0 | 94.9 | +2.4 |
| 14 | U13-86 | Double Ed | 88.3 | +3.1 | – | – | – | – |
| 15 | U13-113 | Double Ed | 94.1 | +4.4 | – | – | – | – |
| 161 | U13-138 | Double Ed | 98.0 | +4.0 | – | – | – | – |
| 17 | U13-157 | Double Ed | 97.1 | +4.8 | 97.8 | +3.8 | – | – |
| 18 | U13-166 | Double Ed | 99.0 | +3.9 | 97.8 | +3.0 | – | – |
| 19 | U13-191 | Double Ed | 96.1 | +4.5 | – | – | – | – |
| 20 | U13-214 | Double Ed | 93.6 | +3.5 | 98.0 | +2.7 | – | – |
| 21 | U13-233.5 | Double Ed | 93.0 | +2.0 | – | – | – | – |
| 22 | U13-253 | Double Ed | 93.8 | +4.8 | 101.8 | +4.0 | – | – |

APPENDIX VII-d, CONTINUED

| NO. | SAMPLE NO. | DEPOSIT | YIELD % | PYRITE $S^{34}S$ (‰) | YIELD % | CHALCOPYRITE $S^{34}S$ (‰) | YIELD % | SPHALERITE $S^{34}S$ (‰) |
|---|---|---|---|---|---|---|---|---|
| 23 | HC-1 | Hidden Creek | - | - | 96.5 | +7.8 | - | - |
| 24 | HC-2 | Hidden Creek | 94.5 | +10.0 | 93.7 | +9.8 | - | - |
| 25 | HC-3 | Hidden Creek | - | - | 86.1 | +8.7 | - | - |
| 26 | HC-4 | Hidden Creek | - | - | 94.8 | +7.6 | - | - |
| 27 | HC-5 | Hidden Creek | - | - | 95.8 | -3.3 | - | - |
| 28 | HC-6 | Hidden Creek | 89.8 | -4.3 | - | - | - | - |
| 29 | HC-7 | Hidden Creek | 85.7 | +6.7 | 104.7 | +5.4 | - | - |
| 30 | HC-8 | Hidden Creek | 95.2 | +6.7 | 96.0 | +6.2 | - | - |
| 31 | HC-9 | Hidden Creek | 90.6 | +2.3 | - | - | - | - |
| 32 | SR-70 | Bonanza | 95.6 | +2.3 | - | - | 93.8 | +1.2 |
| 33 | SR-72b | Bonanza | 98.2 | +1.2 | 96.8 | +1.4 | - | - |
| 34 | SR-74a | Bonanza | 85.6 | +0.2 | - | - | - | - |
| 35 | SR-75 | Bonanza | 90.3 | +2.4 | - | - | - | - |

Contains 12 folded maps.